Narpinder Singh
S. Ananda Babu *Editors*

Climate Crisis and Sustainable Solutions

Strategies for Adaptation, Mitigation and Sustainable Development

Springer

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Editors
Narpinder Singh
Graphic Era (Deemed to be University)
Dehradun, Uttarakhand, India

S. Ananda Babu
Disaster Management Initiatives &
Convergence Society (DMICS)
Hyderabad, Telangana, India

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Preface

In an era marked by unprecedented environmental changes and complex global challenges, safeguarding food and nutritional resilience has never been more critical. This book titled *Securing Sustenance: Climate Adaptation, Vulnerability to Hazards, and the Decarbonization Imperative in Enhancing Food and Nutritional Resilience* is a collection of selected articles presented at the sixth World Congress on Disaster Management held at Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India, during Nov–Dec 2023. This book explores into the multifaceted dynamics that strengthen the stability and sustainability of our food systems in the face of a rapidly changing climate. **The first section** of this book focuses on assessing the global impacts of climate change on food and nutritional security with essential strategies for mitigation. It also explores decadal changes in glacier of Alaknanda basin, Uttarakhand, under warming climate. Additionally, it delves into climate chaos: navigating the dual challenge faced by migrant workers in Bengaluru, India. Furthermore, it examines the effects of algal biodiesel–petrodiesel blends on emissions from IC engines. Finally, it investigates the drought stress on different grains and approaches to alleviate its effects. **The second section**, Sustainable Development Goals and Policies, examines perceptions of climate change and its impacts on local communities along the Noakhali coast in Bangladesh. HVDC submarine cable: A perspective towards accomplishing UN's SDG goals for our Indian marine ecology. **The third section** highlights disaster management and preparedness, focusing on the interplay between fossil fuels and natural disasters, monitoring fire hotspot and aerosol climatology over South Asia using satellite data, mapping and monitoring the Asan watershed using geospatial technology, assessing drought vulnerability in farming communities in the North Central province of Sri Lanka using a community capital framework analysis, and quantifying glacier retreat and elevated lake growth using remote sensing for disaster management in the Western Himalayas. It also explores the role of physiotherapists in disaster management. **The fourth section** focuses on environmental pollution and air and water quality. This includes identification of upwind source regions responsible for pollution episodes over New Delhi during pre-and post-monsoon season. It also examines air quality dynamics in North India, factors militating against solid waste management in Africa, and assesses ozone pollution in the foothills of central Himalayan valley. The **final and fifth section** focuses on ecological impact and conservation, water resources, and agriculture. This section includes a review on the impact of climate change in the Eastern Himalayan state of Sikkim, India, and navigating a legal response to climate change and natural disasters. It also evaluates emerging contaminants (ECs) in water resources, conducts a spatiotemporal assessment, and explores environment-friendly remedies from an Indian perspective. Additionally, it discusses techniques of bioremediation for polluted environments, including an overview, benefits, drawbacks, and future prospects. Furthermore, it examines the potential of Himalayan chir pine biomass as an adsorbent for removing industrial dyes.

Dehradun, Uttarakhand, India Narpinder Singh
Hyderabad, Telangana, India S. Ananda Babu

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We would like to extend our deepest gratitude to all the authors who contributed their chapters. This book would not have been possible without the support and contributions of many individuals. Their expertise and dedication to their respective fields have enriched this volume and made it a comprehensive resource. A special thanks to our peer reviewers, whose valuable feedback and insights significantly enhanced the quality of the content. Their rigorous reviews were instrumental in refining and enhancing the value of the chapters.

We are especially indebted to Prof. Kamal Ghanshala, President of Graphic Era Group of Institutions for his exceptional leadership and unwavering support. His vision and dedication to advancing education and research have been a constant source of inspiration for this work. We are deeply appreciative of his contributions and ongoing commitment to fostering academic excellence.

We are immensely grateful to the editorial team, whose hard work and attention to detail have been invaluable throughout the editing process. Your commitment to excellence has been crucial in bringing this book to fruition.

We also wish to acknowledge the support of Springer, whose faith in this project and professional guidance in navigating the complexities of publication have been invaluable. This book is a testament to the collaborative spirit of the academic community, and we are honored to have worked with such talented and dedicated individuals.

Thank you all.

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Editors and Contributors

About the Editors

Narpinder Singh has effectively shared his research expertise with the scientific community, as evidenced by his impressive total of 20 research papers published in journals of international repute (Food Chemistry, Cereal Chemistry, Journal of Food Science, Food Hydrocolloids, Food Research International, Starch/Starke, Carbohydrate Polymers, LWT-Food Science and Technology, International Journal of Food Science and Technology, Journal of Physical Chemistry C, and ACS Sustainable Chemistry and Engineering). He has also contributed 20 book chapters, 41 review papers, and 3 editorials. His co-authored book titled *Pulse Chemistry and Technology*, published in 2012 by "The Royal Society of Chemistry" is subscribed as a textbook in many Universities. He has an h-index of 94 (Google Scholar) and citations of more than 31,000. Prof. Singh is a fellow of the Royal Society of Chemistry the Cereals and Grains Association (formerly American Association of Cereal Chemists, AACC); the Association of Food Scientists and Technologists (I); the National Academy of Sciences, India; the Indian National Science Academy; and the National Academy of Agricultural Sciences. He is holding J. C. Bose National Fellowship of the Department of Science and Technology, Ministry of Science and Technology, Government of India, for outstanding research performance since 2011. He served as Editor-in-Chief of Journal of Food Science and Technology (Springer) February 2016–May 2019. He served as Guest Editor of special issue on "Proteins Isolates and Hydrolysates: Structure-Function Relation, Production, Bioactivities and Applications for Traditional and Modern High Nutritional Value-Added Food Products" of International Journal of Food Science and Technology, 2021, and Associate Editor of Frontier in Nutrition Section Food Chemistry since 2021. He is recognized as a highly cited researcher for his exceptional research performance, demonstrated by production of multiple highly cited papers that rank in the top 1% for the field and year in Agricultural Sciences by Clarivate in 2021, 2022, and 2023. He is Guest Editor of special issue "Metabolomics Applications in Food Science, Technology and Nutrition," of International Journal of Food Science and Technology, 2024 (Wiley). He has also published articles on metabolomic profiling of cereals and legumes, highlighting the influences of variety, heat stress, and photoperiod on composition, nutritional and processing qualities.

S. Ananda Babu has a PhD from Osmania University (OU), India. He is a societal awareness specialist and contributed numerous books, including several on disaster risk reduction, community resilience, and responses. In addition, Dr. S. Ananda Babu is the Founder President of the Disaster Management Initiatives and Convergence Society (DMICS) and the Convener of the World Congress on Disaster Management (WCDM) established in 2005. In the aftermath of the 2004 Indian Ocean Tsunami, to enhance understanding and awareness among people about the risk of various types and dimensions of disasters and the measures to be taken to reduce the risks, for better preparedness, response, and recovery, the DMICS and the WCDM have taken on the task of creating awareness through multidisciplinary research, publications, and multistakeholder consultations. The World Congress on Disaster Management (WCDM) is a unique initiative of DMICS to bring researchers, policymakers, and practitioners from around the world to a common platform to discuss various challenging issues of disaster risk management. Delegates representing various international, regional, national, state, and local governments, UN bodies, scientific and technical organizations, universities, civil society organizations, the corporate sector, and media attended the Congress. Six editions of the WCDM have been held in cities across India, jointly organized with the respective state governments, under the patronage and leadership of the state's chief minister and with the support of various central government ministers.

Contributors

Nadia Afrin Disaster and Development Organization (DADO), Chittagong, Bangladesh

Sonal Aggarwal Department of Food Science and Technology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

Shazia Akhtar Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

Edris Alam Faculty of Resilience, Rabdan Academy, Abu Dhabi, United Arab Emirates

Department of Geography and Environmental Studies, University of Chittagong, Chittagong, Bangladesh

Ashish Kumar Arya Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

Anjas Asrani Department of Mechanical Engineering, Graphic Era Deemed to be University, Dehradun, Uttarakhand, India

S. Suresh Babu Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, India

Archana Bachheti Department of Food Science and Technology, Graphic Era (Deemed to be University), Dehradun, India

Riya Barthwal Department of Food Science and Technology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

Sourish Bhattacharya CSIR CSMCRI, Bhavnagar, India

Siji Chacko Migrants Resilience Collaborative, Bangalore, India

Vidhi Madaan Chadda Faculty of Law, University of Delhi, Delhi, India

Bhaskerpratap Chaudhary Chandigarh Group of Colleges, Chandigarh, India

L. M. Dharmasiri Department of Geography, Faculty of Social Sciences, University of Kelaniya, Kelaniya, Sri Lanka

Ashish Kumar Dubey Indian Institute of Remote Sensing, ISRO, Dehradun, India

Sai Hari Chandana Ekkirala Amrita School for Sustainable Futures, Amrita Vishwa Vidyapeetham, Amritapuri Campus, Amritapuri, Kerala, India

Monica Gangopadhyay Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

Pavan Gangwar Department of Electronics and Communication Engineering, IMS Engineering College, Ghaziabad, India

Imran Girach Space Applications Centre, Indian Space Research Organisation, Ahmedabad, India

Sanjoy Gorai Thapar Institute of Engineering and Technology, Patiala, India

Rekha Goswami Department of Environment, Graphic Era Hill University, Dehradun, Uttarakhand, India

L. M. A. P. Gunawardhana Faculty of Graduate Studies, University of Kelaniya, Kelaniya, Sri Lanka

Department of Environmental Management, Faculty of Social Sciences and Humanities, University of Sri Lanka, Rajarata, Sri Lanka

S. Harithasree Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad, India

Md Azizul Hoque Disaster and Development Organization (DADO), Chittagong, Bangladesh

Mohammad Mohaiminul Islam Disaster and Development Organization (DADO), Chittagong, Bangladesh

Paul Donald Johnstone Faculty of Resilience, Rabdan Academy, Abu Dhabi, United Arab Emirates

Shefali Juyal Department of Environmental Science, Graphic Era Deemed to be University, Dehradun, India

Yogesh Kant Indian Institute of Remote Sensing, ISRO, Dehradun, India

R. Rachan Karmakar Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

Deepika Kathuria Department of Food Science & Technology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

Ameena Kidwai Migrants Resilience Collaborative, Bangalore, India

Arun Kumar Department of Food Science and Technology, Graphic Era (Deemed to be University), Dehradun, India

Bhartendra Kumar Indian Institute of Remote Sensing (ISRO), Dehradun, India

Neeraj Kumar Roorkee Institute of Technology, Roorkee, India

Pradeep Kumar Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

Rajesh Kumar Department of Chemistry, S.S.J. University, Campus Almora, Almora, India

Krishnendu Kundu Department of Biofuel, CSIR CMERI CoEFM, Ludhiana, India

A. S. Madhusudanacharyulu Department of Physics, Raghu Engineering College, Visakhapatnam, India

Sumon Miah Department of Meteorology, University of Dhaka, Dhaka, Bangladesh

D. Mishra Future Institute of Engineering & Technology, Bareilly, India

Indian Maritime University, Kolkata Campus, Kolkata, West Bengal, India

D. Mitra Indian Institute of Remote Sensing, ISRO, Dehradun, India

Morshed Hossan Molla Young Power in Social Action (YPSA), Chittagong, Bangladesh

Jonathan K. Moses Department of Environmental Science, Graphic Era (Deemed to be) University, Dehradun, India

Swasti Mudgal Department of Food Science and Technology, Guru Nanak Dev University, Amritsar, Punjab, India

Pratibha Naithani Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

Suman Naithani Department of Environment, Graphic Era (Deemed to be University), Dehradun, India

Tanvir Mahtab Nasim Disaster and Development Organization (DADO), Chittagong, Bangladesh

Akanksha Negi Department of Food Science & Technology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

Narendra Ojha Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad, India

Pratima Pandey Indian Institute of Remote Sensing, Dehradun, India

S. Parveen Indian Maritime University, Kochi Campus, Kochi, Kerala, India

Maman Paul Department of Physiotherapy, Guru Nanak Dev University, Amritsar, Punjab, India

Brijesh Prasad Department of Mechanical Engineering, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

Varsha Prem Amrita School for Sustainable Futures, Amrita Vishwa Vidyapeetham, Amritapuri Campus, Amritapuri, Kerala, India

Anita Rajor School of Energy and Environment, Thapar Institute of Engineering and Technology, Patiala, India

M. M. Ranagalage Department of Environmental Management, Faculty of Social Sciences and Humanities, University of Sri Lanka, Rajarata, Sri Lanka

S. N. Remya Amrita School for Sustainable Futures, Amrita Vishwa Vidyapeetham, Amritapuri Campus, Amritapuri, Kerala, India

Lokesh K. Sahu Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad, India

Savita Graphic Era Hill University, Dehradun, India

Nilanjana Sengupta Indian Institute of Remote Sensing, ISRO, Dehradun, India

Kiran Sharma Graphic Era (Deemed to be University), Dehradun, India

Rachna Sharma Roorkee Institute of Technology, Roorkee, India

Santosh Sharma Department of Management, The ICFAI University Sikkim, Gangtok, India

Aoujasva Veer Vikram Singh University of Delhi, Delhi, India

Gaurav Singh Department of Civil Engineering, (Graphic Era Deemed to be University), Dehradun, India

Narendra Singh Aryabhatta Research Institute of Observational Sciences, Nainital, India

Narpinder Singh Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

Sandhya Singh Indian Institute of Remote Sensing, Dehradun, India

Shuchita Srivastava Indian Institute of Remote Sensing (ISRO), Dehradun, India

Soumya Tiwari Migrants Resilience Collaborative, Bangalore, India

Joselyn B. C. Toomey Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

Vijay Tripathi Department of Microbiology, Graphic Era (Deemed to be University), Dehradun, India

Md Imtiaz Uddin Department of Spatial Information & Modelling, Leibniz Institute of Ecological Urban and Regional Development, Dresden, Germany

Shivangi Vashishta Indian Institute of Corporate Affairs, Haryana, India

Vrince Vimal Graphic Era Hill University, Dehradun, India

Part I

Climate Change and Adaptation

Assessing the Global Impacts of Climate Change on Food and Nutritional Security: Essential Strategies for Mitigation

Arun Kumar, Swasti Mudgal, and Narpinder Singh

1 Introduction

Climate change can have significant and extensive influences on food and nutritional security globally. These climate shifts can severely disrupt agricultural output, diminishing crop yields and ultimately resulting in food shortages and price fluctuations. The rising temperatures and altered precipitation patterns have already been identified as significant factors contributing to decreased crop productivity. For instance, heat stress can affect the growth of staple crops such as rice and wheat, which are critical for food security. Heat stress affects wheat productivity and grain quality (Singh et al., 2021). High daytime temperatures accelerate rice plant aging, shorten the grain-filling period, and impair grain formation, consequently decreasing rice production (Krishnan et al., 2011; Prasad et al., 2006). Changes in the amylose content and amylopectin ratio were observed with increasing NTAT (nighttime air temperature) (Cooper et al., 2008; Counce et al., 2005), attributing to a decreased nutrient supply to the endosperm, slow starch granule growth, and an irregular structure (Fitzgerald & Resurreccion, 2009). Counce et al. (2005) depicted that this disruption in starch formation was linked to enzymatic activity disturbance. Tamaki et al. (1998) studied the effects of simulated nighttime thermal levels (14, 20, and 26 °C) in a greenhouse on amino acid content in cultivars with high and low

A. Kumar · N. Singh (✉)
Department of Food Science and Technology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India
e-mail: vicechancellor@geu.ac.in; narpinders@yahoo.com

S. Mudgal
Department of Food Science and Technology, Guru Nanak Dev University, Amritsar, Punjab, India

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protein levels. Cultivars at 26 °C showed decreased free amino acids compared to lower thermal levels. Additionally, higher temperatures increased the protein-to-starch ratio without changing the total protein amount (Fitzgerald & Resurreccion, 2009). Some rice varieties exposed to NTAT of 30 °C showed increased total lipids content in comparison to those at 18, 22, and 26 °C (Cooper et al., 2008). Higher NTAT levels, as indicated by Lanning et al. (2012), led to greater lipids accumulation but decreased protein and starch levels. Since starch constitutes a significant portion of milled rice, NTAT-induced changes affect its cooking properties. Proteins and lipids both contribute to altering the characteristics of cooked rice (Fitzgerald & Resurreccion, 2009; Han & Hamaker, 2001; Hamaker & Griffin, 1993). Certain proteins, linked to amylose via disulfide bonds within starch granules, influence the texture and sensory attributes of cooked rice (Hamaker & Griffin, 1993). Lipids impact starch swelling and viscoelastic properties by forming complexes with the helical structure of amylose (Liang et al., 2002). Espeland and Kettenring (2018) depicted that as global temperatures rise, the climate shifts significantly, leading to severe abiotic stress. These environmental changes pose numerous threats to existing crop species in their natural habitats. Elevated carbon dioxide levels and drought together with heat are the predominant stresses under field conditions and significantly affect plants (Pereira, 2016). Heat stress impacts grain production and yield, while cold stress causes sterility, and drought stress affects plant morphophysiology (Salehi-Lisar & Bakhshayeshan-Agdam, 2016; Barlow et al., 2015). Adapting to these changes can be costly and challenging for farmers. Warmer temperatures may lead to increased pest and disease prevalence, negatively impacting crops and livestock. Climate change affects crop production through direct, indirect, and socio-economic pathways, as depicted in Fig. 1. This can result in significant crop losses and reduced agricultural productivity. Boyer (1982) documented a significant reduction in crop yield, up to 70%, due to climate change. According to FAO report,

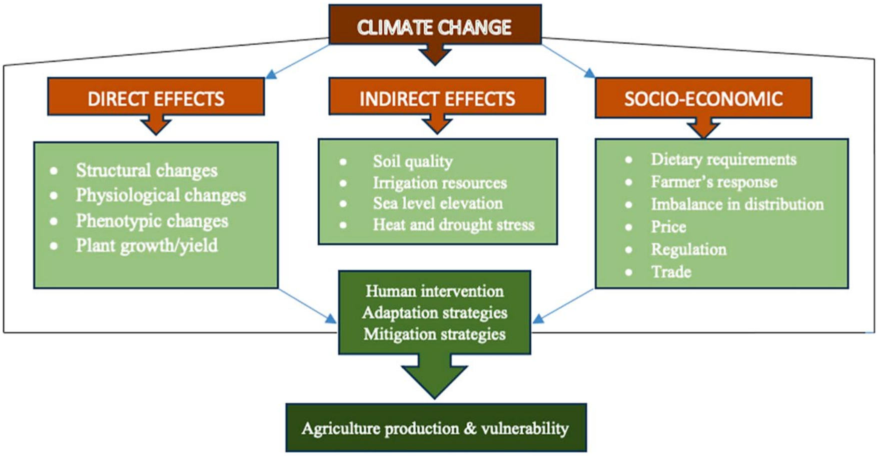

Fig. 1 Climate change impacts crop production through direct, indirect, and socioeconomic pathways

in 2007 the meteorological conditions affect all cultivated regions globally, exclusively 3.5% of areas immune to ecological limitations (Van Velthuizen, 2007). Accurately estimating the impact of abiotic stresses on crop yield is challenging, but it is widely acknowledged that these stresses significantly affect crop production, depending on the extent of damage across the total cultivated area (Tebaldi & Lobell, 2018). Table 1 presents the global repercussions of climate change on wheat and rice crops, as evidenced by prior literature. In the future, major crop productivity is expected to decline globally due to factors such as global warming, water scarcity, and other environmental consequences. Climate crises can exacerbate water scarcity in many parts of the world. Reduced water availability for irrigation and other agricultural practices can directly impact crop production and food security. This can make food less affordable and accessible for vulnerable populations, impacting their nutritional status. For example, elevated carbon dioxide levels can reduce the mineral and protein contents of crops, potentially leading to deficiencies

Table 1 Impact of climate change on the production of agricultural crops

Agricultural crops	Variation in production	Probable cause	Geographical location	References
Wheat	6.9% decrease	Rising temperature	Major wheat-producing countries (USA, France, Russia, India, China)	Zhao et al. (2017)
	5–13% decrease	Drought events in early season	US Midwest	Liu and Basso (2020)
	2–18% decrease	Drought events in late season		
	10.2% decrease	For each 1 °C rise in mean temperature in spring	China	Tao et al. (2006)
	7% decrease	2 °C increase in temperature	Globally	Easterling et al. (2007)
	34% decrease	4 °C increase in temperature	Globally	
	36% decrease	Heat stress	University of Sydney, Narrabri	Ullah et al. (2020)
Rice	3.2% decrease	Rising temperature	Major rice-producing countries (India, China, Bangladesh, Indonesia, Vietnam)	Zhao et al. (2017)
	12.6–22% increase	CO_2 elevation	Gwangju, Korea	Kim et al. (2013)
	Decrease by 2% and 5%, respectively	Temperature rise by 1.5 and 2.0 °C	China	Chen et al. (2018)
	Decreased by 10.9% in moderately flooded	Average temperature rise by 2.0 °C	Northeast China	Saud et al. (2022)

in essential nutrients. Climate change can lead to increased heat stress, vector-borne diseases, and waterborne diseases, all of which can affect the health and nutritional status of vulnerable populations (Ebi & Loladze, 2019). Furthermore, global efforts to actions in alleviate climate change through reducing greenhouse gas emissions are crucial in preventing the most severe consequences for food and nutritional security around the world. This article delves into the multifaceted challenges and potential consequences of the influence of climate change on worldwide food and nutrition security, as well as the strategic approaches required to mitigate these impacts effectively.

2 Effects of Climate Change on the Nutritional Composition of Agricultural Crops

Climate change can impact the nutritional composition of agricultural crops through various mechanisms. Variations in thermal levels, rainfall patterns, and levels of atmospheric carbon dioxide can alter plant physiology, growth, and development, ultimately influencing the nutritional content of crops. Moreover, elevated atmospheric carbon dioxide, a key climate change factor, can impact crop nutritional quality. Research indicates that rising carbon dioxide levels might alter nutrient concentrations, impacting the balance of macronutrients (carbohydrates, fats and protein) and micronutrients (vitamins along with minerals) in crops (Myers et al., 2014). Rising temperatures can influence the timing of plant development, affecting the synthesis and accumulation of certain nutrients. Temperature changes may also impact water availability and nutrient uptake by plants, potentially altering nutrient concentrations (Myers et al., 2014). Variations in precipitation patterns and increased occurrence of extreme weather events, such as droughts, can result in water scarcity. Water stress can affect crop yields and nutrient absorption, potentially impacting the nutritional content of crops (Lobell & Gourdji, 2012).

2.1 Starch Content

Starch formation involves a complex process that relies on multiple enzymes crucial throughout grain filling. Under drought conditions, there is often an acceleration in grain filling but a reduction in total starch accumulation due to shortened grain-filling periods and modified enzyme function (He et al., 2012). Drought stress in rice significantly reduces the grain starch content, with reports indicating a 38% decrease in the final starch content during the reproductive stage under field settings (Emam et al., 2014). The decrease in starch content caused by reduced sugar movement from the stem to developing seeds affects fatty acid makeup, which is fundamental to oil formation (Sehgal et al., 2016). Interestingly, simultaneous exposure to drought and Se (selenium) not only offset the impact of drought stress but also increased starch levels by 14% in comparison with control. In wheat, heat stress during the reproductive phase in controlled environments led to a substantial reduction in starch content ranging from 23% to 35% (Zahedi et al., 2004; Altenbach et al., 2003). Increased levels of CO_2 had a significant impact on grain quality characteristics, leading to higher levels of chalkiness (ranging from 69% to 83%) and amylose content (increasing by 18–37%). When exposed to both elevated carbon dioxide and heat stress, the proportion of chalky grains further increased in some rice varieties. When rice is exposed solely to elevated carbon dioxide, grain quality decreases, and the combination of elevated carbon dioxide and heat stress exacerbates the adverse effects on both grain nutrient content and quality. Analysis of correlations revealed a negative association between grain minerals and both chalkiness and amylose content (Chaturvedi et al., 2017).

2.2 Protein Content

Rising temperatures, altered precipitation patterns, and increased greenhouse gas concentrations are among the key climate factors that can negatively impact the protein content of agricultural crops. The influence of climate change on cultivated crops extends beyond just transformation in thermal levels and precipitation regime; it also affects the nutritional composition of these crops, including their protein content. Several studies have explored the connection between climate change and protein levels in various crops, highlighting the complex and multifaceted nature of this phenomenon. For example, a study by Myers et al. (2014) found that elevated temperatures can lead to a decrease in the protein content of wheat. Heat stress during the grain-filling period negatively affects the synthesis of proteins, ultimately reducing the nutritional quality of harvested grains. Rising atmospheric carbon dioxide levels, another consequence of climate change, can impact protein content. Some studies suggest that increased carbon dioxide concentrations may lead to a dilution effect on the protein content of crops (Taub et al., 2008). This occurs because higher carbon dioxide levels can stimulate plant growth, but the proportional increase in protein may not match the increase in overall biomass. Chaturvedi et al. (2017) independently conducted field experiments to evaluate the potential effects of elevated carbon dioxide levels, either individually or in conjunction with heat stress, on some varieties of rice. These findings indicate that elevated carbon dioxide levels significantly reduce protein content by 4% and alter the composition of grain mineral nutrients across both cultivars. Research conducted by Wang et al. (2011) and Myers et al. (2014) additionally showed that elevated carbon dioxide levels caused decreased grain protein concentrations and shifts in grain mineral makeup. The findings of studies by Myers et al. (2014), DaMatta et al. (2010), and Wang et al. (2011) involving rice and wheat under elevated carbon dioxide conditions consistently demonstrate a decrease in grain nutrient content. Fahad et al. (2017) reported that changes in rainfall trends and a higher occurrence of droughts associated with climate change can also impact protein content. Drought stress can reduce the availability of water for plants, affecting their ability to absorb nutrients and synthesize proteins. Different crop varieties respond differently to climate stressors. Some varieties may show resilience to certain climate-induced changes, while others may be more vulnerable. Understanding the genetic diversity within crop species is crucial for developing climate-resilient varieties with optimal nutritional profiles (Dwivedi et al., 2017).

2.3 Fat Content

Climate change can have profound effects on various aspects of agriculture, including the fat content of crops. Changes in temperature, precipitation patterns, and atmospheric carbon dioxide levels can influence the composition of crops, including their fat content. Higher temperatures associated with climate change can affect the lipid metabolism of plants. Investigations have demonstrated that elevated temperatures can affect the function of genes associated with lipid synthesis and metabolism in agricultural crops, potentially altering fat content (Degenkolbe et al., 2012). Oilseeds, such as soybeans and canola, are particularly sensitive to temperature changes. Warmer temperatures can lead to changes in the fatty acid composition of oils produced by these crops, affecting their nutritional quality (Scherer, 2001). Changes in precipitation patterns, including drought and water scarcity, can induce stress on crops. Water stress can influence the synthesis of lipids and oils in plants, potentially leading to alterations in fat content (Upchurch, 2008). Changes in precipitation can also affect soil nutrient availability, further influencing the nutritional composition of crops, including fat content (Lobell et al., 2014). Increasing atmospheric carbon dioxide levels, a key driver of climate change, can have complex effects on plant metabolism. Some studies suggest that elevated carbon dioxide levels can stimulate the production of carbohydrates in plants, which may subsequently influence the synthesis of lipids (Long et al., 2006). Research has indicated that oilseed crops may respond differently to elevated carbon dioxide levels, with potential variations in oil content depending on the specific crop and environmental conditions (Ainsworth & Rogers, 2007). The response of different crops to climate change can vary based on species-specific characteristics. Research on rice has shown that elevated temperatures may reduce the lipid content in rice grains, affecting the nutritional quality of this important staple (Liu et al., 2021).

2.4 Micronutrients

The environmental stress resulting from climate change and the promotion of eco-friendly agricultural practices can disrupt the production of minor grain compounds alongside essential compounds such as starch and protein (Marion & Saulnier, 2020). Micronutrients are essential for facilitating the growth, development, and functionality of both humans and plants. Despite their beneficial effects, micronutrient deficiencies pose significant risks to crop yield and nutritional quality, ultimately impacting human health and well-being (Nakandalage & Seneweera, 2018). Previous research has strongly associated increased carbon dioxide levels with a decline in grain protein content and alterations in the composition of grain minerals

(Myers et al., 2014; Wang et al., 2011; Taub et al., 2008). Investigations focusing on rice and wheat cultivated under high carbon dioxide concentrations have consistently shown an overall decrease in the concentration of nutrients in the grains (Myers et al., 2014; Wang et al., 2011; DaMatta et al., 2010; Taub et al., 2008). Across various cultivars, both macro- and micronutrients displayed a reduction ranging from 4% to 34% under conditions of elevated carbon dioxide alone or in combination with high temperatures compared with the control levels of elevated carbon dioxide. Under increased CO_2, some varieties showed the paramount reduction in Mg (18%) and Fe (20%), with the lowest Cu reduction (5%) and Mn reduction (4%), respectively. Conversely, under increased CO_2 and high temperature, some varieties exhibited the highest Mn reduction (34%) and Cu reduction (31%), respectively (Chaturvedi et al., 2017). Malnutrition involves insufficient protein intake and deficiencies in micronutrients such as iron, zinc, and selenium and remains a significant issue in underdeveloped regions, contributing to various diseases. Several staple foods inherently lack adequate micronutrients either because of insufficient quantities or poor bioavailability. Climate change exacerbates this issue of micronutrient deficiency that already exists (Myers et al., 2014; Scheelbeek et al., 2018). Specifically, climate change, driven by increased carbon dioxide concentrations, temperature fluctuations, and altered water availability, affects how plants take up and utilize micronutrients, albeit to varying degrees and in different directions (Nakandalage & Seneweera, 2018). Heat stress, another consequence of climate change, further compounds nutritional challenges. Elevated temperatures disrupt metabolic processes, leading to reduced protein synthesis and increased accumulation of antinutrients, such as phytic acid. These antinutrients hinder the bioavailability of essential minerals such as iron and zinc, exacerbating the risk of micronutrient deficiencies (Dhaliwal et al., 2022). Climate change-induced factors such as altered rainfall patterns, soil degradation, and increased temperature can affect the availability and uptake of various minerals (such as magnesium, calcium, and selenium) essential for crop nutrition. Changes in soil quality and water availability can influence the ability of plants to absorb these minerals, impacting their concentrations in wheat and rice grains. Elevated levels of atmospheric carbon dioxide due to climate change have been linked to decreased concentrations of Zn and Fe in wheat and rice grains. Studies have shown that increased carbon dioxide levels can lead to reduced uptake and translocation of these minerals in plants, resulting in lower concentrations in the edible parts of crops (Nakandalage & Seneweera, 2018). There is ongoing research on the probable outcomes of atmospheric alterations in other vitamins found in wheat and rice, such as B vitamins (e.g., thiamine and riboflavin). Changes in environmental conditions, including temperature, water availability, and soil quality, can influence the synthesis and accumulation of these vitamins in grains, although specific effects may vary based on the vitamin type and plant species (Smith & Myers, 2019). Climate change can impact the concentration of beta-carotene, a precursor of vitamin A, in crops such as rice. Variations in temperature, water availability, and carbon dioxide levels can affect the synthesis of beta-carotene in rice grains, potentially impacting the nutritional quality of rice as a source of vitamin A (Rezvi et al., 2023).

3 Strategies to Combat and Ameliorate the Effect of Climate Change on Crops

Variations in climate have a profound and enduring impact on the nutritional composition and yield of crops, significantly affecting global food security. Severe weather conditions such as droughts, floods, high temperatures, increased carbon dioxide levels, greenhouse gas production, and heavy rainfall threaten food security and safety (Raza et al., 2019). These conditions directly disrupt the agricultural environment and indirectly strain income growth and distribution, increasing the demand for agricultural products. The rise in temperature has notably reduced the production of major crops worldwide (Tito et al., 2018), posing a significant threat to food security, especially considering the rapid increase in the global population (Rogelj et al., 2016). Malnutrition affects approximately 815 million people, undermining sustainable development efforts aimed at eradicating hunger pangs by 2030 (Richardson et al., 2018). With the projected population reaching around 9 billion by 2050, the demand for food is estimated to surge by about 85% (FAOSTAT, 2017). Current agricultural practices with low diversity and high input concentrations, coupled with crop sensitivity to environmental changes, exacerbate the effects of climatic influences (Reckling et al., 2018). Therefore, addressing and adapting to these weather variations is an urgent global priority. Developing climate-resilient crop varieties, improving irrigation systems, adopting sustainable agricultural practices, and curtailing greenhouse gas emissions are crucial strategies to safeguard the nutritional integrity and yield of these crucial crops.

3.1 Crop Adaptation Methodology

Recent studies have explored farmers' strategies to mitigate the effects of climate change on crop adaptation, such as adjusting planting/harvesting schedules, choosing shorter life cycle crop varieties, adopting crop rotation, improving irrigation, and diversifying cropping. These approaches show notable benefits in enhancing crop adaptability under climatic stress (Deligios et al., 2019; Duku et al., 2018; Marcinkowski & Piniewski, 2018; Teixeira et al., 2018). The crop adaptability approach includes the utilization of plant management methodologies aimed at augmenting crop growth amidst diverse environmental stressors. Significantly, the selection of optimal sowing times, planting densities, and precise irrigation practices serve as pivotal techniques for mitigating the impacts of weather-induced stresses (Ali & Erenstein, 2017; Shah & Wu, 2019). Adjustment of sowing schedules, utilization of drought-resistant cultivars, and diversification of cultivated crop varieties are critical strategies for mitigating the risks posed by climatic variability. These approaches significantly enhance the adaptability of crop plants, ensuring food safety and security in the face of environmental challenges (Klepeckas et al., 2020).

3.2 Biotechnological Applications

Biotechnological tools have immense potential in mitigating the adverse impacts of climate change on crops. Through genetic modification, scientists can develop crop varieties that are resilient to extreme weather conditions, such as drought-resistant or heat-tolerant strains. Additionally, biotechnology aids in enhancing crop productivity by optimizing traits such as disease resistance, nutrient efficiency, and yield under stress. Techniques such as gene editing allow for precise alterations in crop genomes, expediting the breeding process for resilient varieties. Moreover, biotechnological advancements enable the creation of climate-smart crops that contribute to sustainable agriculture by reducing greenhouse gas emissions and minimizing resource inputs, ultimately fostering food security amidst changing environmental conditions (Munaweera et al., 2022). The genetic divergence analysis method holds considerable significance in the development of novel cultivars, leveraging insights derived from genetic distances and similarities (Raza et al., 2018, b). Plant breeding offers a dynamic approach to crop improvement amid diverse environmental stresses. This approach serves as a promising avenue to ensure nutritional security and integrity despite hostile weather fluctuations by aiding plants overcome multifarious stresses during indispensable stages of growth through the development of stress-resistant cultivars (Blum, 2018). Genetic studies often rely on landraces as crucial sources. For instance, certain wheat landraces preserved in data banks harbor extensive genetic diversity, making them valuable resources for stress resistance. These landraces hold cultivars that exhibit adaptability to diverse environmental stresses (Lopes et al., 2015).

3.3 Crop Management

Intercropping, especially with grain-legume combinations, is a smart approach amid climate change. Compared with growing crops alone, it has multiple advantages, such as stable yields, efficient resource use, and reductions in weeds, pests, and diseases. For cereals, this mixture also increases protein content and minimizes nitrogen leaching. Building seed banks is vital in unpredictable environments, offering a practical way to replant crops lost due to disasters or extreme climate events. It supports plant dynamics by allowing different germination strategies to cope with varying yearly growing conditions (Raseduzzaman, 2016; Kumawat et al., 2022). Farmers using sequential cropping and adjusting planting times based on the climate experience low crop yield loss. For small farmers in Kenya, adopting agroforestry helps reduce greenhouse gas buildup, aiding in climate adaptation (Verchot et al., 2007). Simple methods such as altering rice drying methods, adjusting livestock diets, and improving nitrogen use in farming can reduce greenhouse gas emissions. Basic changes such as tweaking planting schedules and using different crop varieties can also lessen the impact of climate change (Aggarwal, 2008). Getting technology out to farmers is crucial in how they respond to climate shifts. It is key to focus on linking to markets and supporting public research and skill development (Lybbert & Sumner, 2012).

3.4 Conservation of Resources

Key conservation-focused technologies incorporate strategies such as in situ water conservation, rainwater harvesting, efficient irrigation water use, sustainable agriculture, eco-friendly agronomy and irrigation, and the utilization of low-grade water. Suggested approaches include remote sensing-based characterization of biophysical and socioeconomic resources, integrated watershed development, strategies to enhance rainwater utilization efficiency through harvesting, preservation, recycling, and emergency crop planning to alleviate yield reductions amid drought or flood seasons (Venkateswarlu & Shanker, 2009). Zero tillage (ZT) has notably reduced water demand in rice-wheat cropping systems across more than a million hectares in the Indo-Gangetic Plains. Adopting ZT technology has enabled farmers to achieve higher yields and reduce production costs. Additionally, ZT contributes to mitigating greenhouse gas emissions by converting carbon dioxide into oxygen and carbon, enriching soil organic matter (Jat et al., 2019). Bed planting, widely embraced in the Indo-Gangetic Plains, has proven to be a successful conservation method (Jat et al., 2019). Its benefits include enhanced water utilization efficiency, minimal waterlogging, improved access for interrow cultivation, effective weed management and fertilizer application, enhanced stand establishment, and reduced crop lodging.

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Decadal Changes in Glaciers in the Alaknanda Basin (Uttarakhand) Under Warming Climate

Sandhya Singh and Pratima Pandey

1 Introduction

Water is the fundamental source of life, and life cannot exist without it (Fetter, 2014). Rivers play a crucial role as the primary suppliers of fresh water, while glaciers are vital for sustaining the world's major, year-round flowing rivers. In the Himalayan region, the primary source of major rivers is glaciers, and both ice and snow hold a substantial portion of the freshwater resources on Earth (Singh & Jain, 2002). The Himalayan region experiences natural disasters due to its extreme climatic conditions resulting from its high altitudes and geological vulnerabilities brought about by geotectonic processes. The causes and effects of climate change, which are influenced by both natural and anthropogenic factors (Crowley, 2000; Hansen et al., 1998; Stoffel et al., 2015), have grown to be a significant scientific concern. It is widely recognized that glaciers serve as markers of climate change, and their variations can be directly interpreted as warning signals of climate shifts (Rupper & Roe, 2008; Sagredo & Lowell, 2012). The Himalayan region is experiencing the impacts of climate change, which are evident in the fast-paced shifts in glacial cycles that have led to the emergence of numerous glacial lakes (Fujita et al., 2001).

An expanse of water created when glaciers melt is known as a glacial lake, which is typically found in low-lying areas within glaciated regions. These lakes may sometimes be distant from the current glacial areas, as Mool et al. (2001) mentioned. There has been a notable rise in both the quantity of these lakes and the amount of water they store. These lakes are often situated close to the glacier terminus and bordered by natural dams formed by lateral or end moraines, as discussed by Kattelmann (1997). The increasing land surface temperature (LST) as a result of climate change has increased the vulnerability of glacial lakes to bursting. There has

S. Singh (✉) · P. Pandey
Indian Institute of Remote Sensing, Dehradun, India

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been a rise of 2, 2.8, and 1.8 °C in the seasonal mean, maximum, and minimum temperatures, respectively (Shekhar et al., 2010). In June 2013, the state of Uttarakhand in India experienced its most recent flash flood and glacial lake outburst flood (GLOF). During the period from June 15 to 17, 2013, the entire state received an excess of 400 mm of intense rainfall (Dobhal et al., 2013). This extreme rainfall event led to significant surface runoff, runoff from snowmelt, and bursting of the Chorabari moraine-dammed lake. These factors combined to cause extensive flooding throughout the major river channels across Uttarakhand. The resulting floods inflicted severe damage on the state as a whole, with a particularly devastating impact on the famous pilgrimage route from Kedarnath to Sonprayag. Additionally, all settlements at Rambara station were completely washed away, resulting in a significant loss of human life.

Since 1998, a significant number of efforts have been made to mitigate various issues (Andreassen et al., 2008). A comprehensive investigation of glaciers in India began with an inventory of glaciers in a continuous section of the Himalayan Range (Raina, 2009). The Survey of India (SOI) released the first topographic maps of the glaciated Himalayan region at a 1:50,000 scale in the 1960s, utilizing aerial photographs as a basis (Mool et al., 2001). In the twenty-first century, the Space Application Centre and the International Centre for Integrated Mountain Development (ICIMOD) (Bajracharya & Mool, 2007) conducted distinct glacier assessments for the entire Himalayan region. The SAC inventory covered the years 2004–2008, while the ICIMOD inventory spanned the years 1999–2005.

Several studies have addressed the topic of glacial lake outbursts. Since 1850, Himalayan glaciers have generally been retreating (Mayewski & Jeschke, 1979), and recent studies have shown that for many of them, the rate of retreat is increasing. On the glacier snout fluctuation of the Himalayan glaciers, numerous people have conducted extensive research. However, during the past three decades (Raina, 2009), it appears that the rate has dramatically increased. Due to the glacier's various topographical features, the surface velocity and ice thickness as measured by satellites vary spatially. The findings of Pandey et al. (2021) are consistent with the behaviour of glaciers around the world, showing that under a scenario of extreme climate change, glaciers recede quickly and glacial lakes expand more quickly. Furthermore, the findings point to a large decline in glacier area and a direct connection between glacier melting and lake variations.

The most difficult aspect of glacier research lies in obtaining field data consistently and at regular intervals over time. Since continuous field monitoring is often not feasible, remote sensing plays a crucial role in supporting glacier studies. With advancements in remote sensing techniques facilitated by cloud-based platforms, along with the use of geospatial tools and algorithms, monitoring has become more robust. Glaciers need continuous monitoring at higher spatial and temporal scales. Surface movement serves as an effective indicator of overall glacier motion. It is imperative to study and comprehend glacier dynamics, given their critical role as the primary source of freshwater for downstream regions. This understanding is crucial for proper management and policy-making (Badhyopadhyay & Gyawali, 1994). Furthermore, they can be used to study palaeoclimate, as ice cores preserve isotopic and chemical variations and reflect past atmospheric temperature, composition, and climate patterns (Liang et al., 2015). Additionally, glacier movements, including their advancement and retreat, pose a constant threat of potential outburst flooding (Sethia et al., 2018; Yao et al., 2013).

The primary goal of this research is to examine how glaciers have responded to ongoing climate changes over the period from 2000 to 2020. In this study, based on the multi-source remote sensing images such as LANDSAT TM/ETM+ OLI, we produced an inventory of glaciers for the Alaknanda Basin for 2000, 2013, and 2020 to analyse their distribution patterns and dynamic changes to assess the health of glaciers, parameters such as their size, and the extent to which their snouts have retreated. Additionally, this study seeks to comprehend why glaciers within the same geographic region might display varying responses to these changes, taking into account both climate and topographical factors. There are often terminological terms in studies related to lake outburst floods, as noted by Korup and Tweed (2007). The primary terminology is defined in Table 1.

2 Materials and Methods

2.1 Materials

Since the beginning of their availability, satellite data have been extensively employed for studies of glaciers. This study makes use of multi-temporal satellite data from 2000, 2013, and 2020 for the analysis. Various Landsat imagers, including the Enhanced Thematic Mapper (ETM+) and Operational Land Imager (OLI), are employed for this purpose, with data obtained from the USGS Earth Explorer. The study area is covered by a single Landsat scene, and the selection of satellite images is based on specific criteria: (1) images with minimal seasonal snow cover and cloud cover and (2) the ability to identify glaciers in all selected satellite images,

Table 1 Terminology definition

Terms	Definition	Sources
Lake outburst flood (LOF)	Abrupt release of water (some of it) that was previously contained in the lake	Korup and Tweed (2007)
Glacial lake outburst flood (GLOF)	A flood triggered by the release of water from any type of glacial lake	Richardson and Reynolds (2000)
Glacier flood	A glacial lake outburst flood (GLOF) stemming from an ice-dammed lake	Richardson and Reynolds (2000), Clague and O'Connor (2015)
Cause of GLOF	Immediate cause of a glacial lake outburst flood (GLOF)	Emmer and Cochachin (2013)
Mechanism of GLOF	The method or manner in which water is discharged from the lake	Emmer and Cochachin (2013)

Table 2 Detailed information about satellite data used to monitor glaciers

Satellite	Sensor	Acquisition date	Radiometric resolution	Resolution (m)	Source
LANDSAT 7	Enhanced Thematic Mapper (ETM+)	Sep 2000	8 bit	30/15	USGS https://earthexplorer.usgs.gov/
LANDSAT 8	Operational Land Image (OLI)	30 Sep 2020 and 2013	12 bit	30/15	USGS https://earthexplorer.usgs.gov/

prioritizing those captured during the ablation period. Further details about the satellite imagery used can be found in Table 2.

Path and row number: 148-39.

2.2 Methodology

2.2.1 Season Selection

In order to properly display glaciers and permanent snow cover, the season must be chosen when the seasonal snow cover is the lowest. The time between the middle of August and September is optimal for glacier investigations. Consequently, satellite pictures from this time period were employed in the research.

2.2.2 Glacier Delineation

Near the ablation zone and the snout of Himalayan valley glaciers, a significant amount of debris is usually present (Shroder et al., 2000). Figure 1 depicts the flow chart of the methods used. To generate an inventory, it is essential to distinguish between snow patches and small glaciers (<1 km^2), as snow can build up on mountain slopes and ridges for only a few years.

By visual interpretation or by applying the threshold value (<0.02 sq. km), we can eliminate snow patches.

2.2.3 Clean Ice Glacier Mapping

We use the normalized difference snow index (NDSI) for clean ice glacier mapping. NDSI uses two contrasting bands: short wave infrared (SWIR) and green spectra. Hall and Riggs (1995) introduced the NDSI technique for the purpose of detecting snow cover. This indicator offers a useful comparison between the surrounding area at the terminus point and the bare ice. By careful visualization, the NDSI threshold value (>0.4) for the histogram and sampling values is utilized to identify clean ice glaciers (Fig. 2).

The mapping of debris covers on glaciers encompassed the entire region defined by the glacier outlines in the RGI (Pfeffer et al., 2014). Debris-free ice was

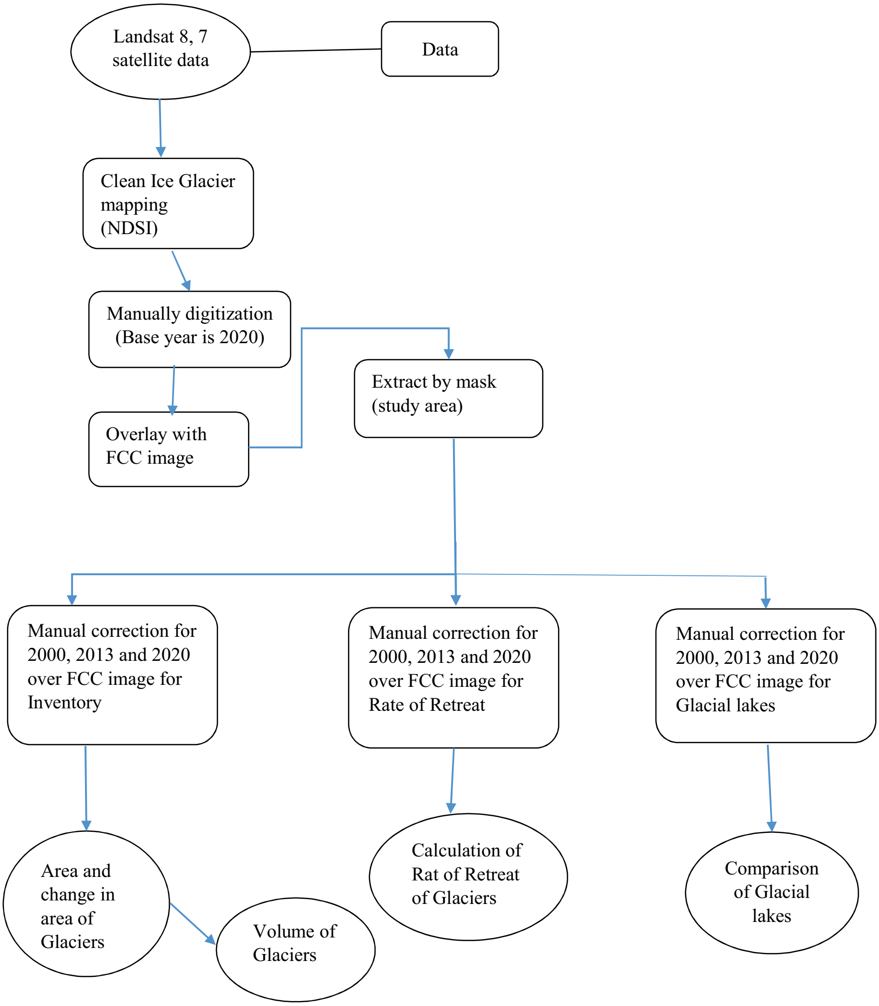

Fig. 1 Flow chart of the methodology

differentiated from ice covered with debris using a normalized difference snow index (NDSI).

$$\text{NDSI} = (\text{Green} - \text{SWIR}) / (\text{Green} + \text{SWIR})$$

2.2.4 Glacier Retreat

In order to study glacier retreat, a band of stripes is drawn parallel to the glacier's primary flow direction. To calculate the length change, the average length from the point where the stripes intersect the glacier outlines is calculated for each image

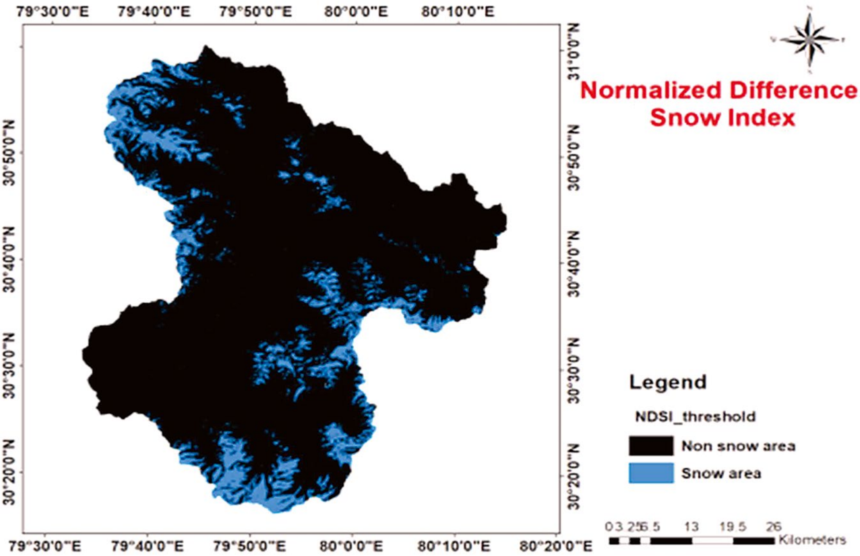

Fig. 2 Clean ice glacier mapping

independently. Based on their size and form, the mapped glaciers were divided into categories. The area ranges were 1, 1–20, and >20 km$^{2.}$

3 Study Area

The Alaknanda Basin covers ~1229 sq. km and has ~407 glaciers (Bhambri et al., 2011). The Dhauliganga River, a part of the Alaknanda Basin, was chosen for the study region (Fig. 3). The extent of the river lies between latitude 30°15′N-30°34′N and longitude 79°30′E-0°15′E. The Dhauliganga River is 82 km long and rises from Parbat Glacier at an altitude of 5070 m (16,630 ft in the Niti Pass) (Thakur et al., 2016) in the Chamoli District, Uttarakhand. The Dhauliganga River is a stream that flows in the southwest direction and joins with Alaknanda at Vishnuprayag and Bhagirathi. At a height of 4663 m, the mouth of two merging glaciers, Raikhana Glacier and East Kamet Glacier, forms a moraine-dammed lake that serves as the Dhauliganga River source. It is situated in India's Uttarakhand region of the north-west Himalayas. According to Jain et al. (2012), the basin's total size is 4508 sq. km. East Kamet Glacier and Parbat Glacier, both located in Uttarakhand's Chamoli district, are ancestors of Raikhana Glacier and Kamet Parbat (7756 m), respectively. According to previous research, there are 62 supraglacial and lateral moraine-dammed lakes in the Dhauliganga catchment area. Vasudhara Tal is the name for the possible risk lake in their ablation zone, which is the Dhauliganga River's source, also referred to as the Kamet Base Camp. It is located at an elevation of 4663 m. Dhauliganga is one of the Alaknanda's significant tributaries, along with Nandakini,

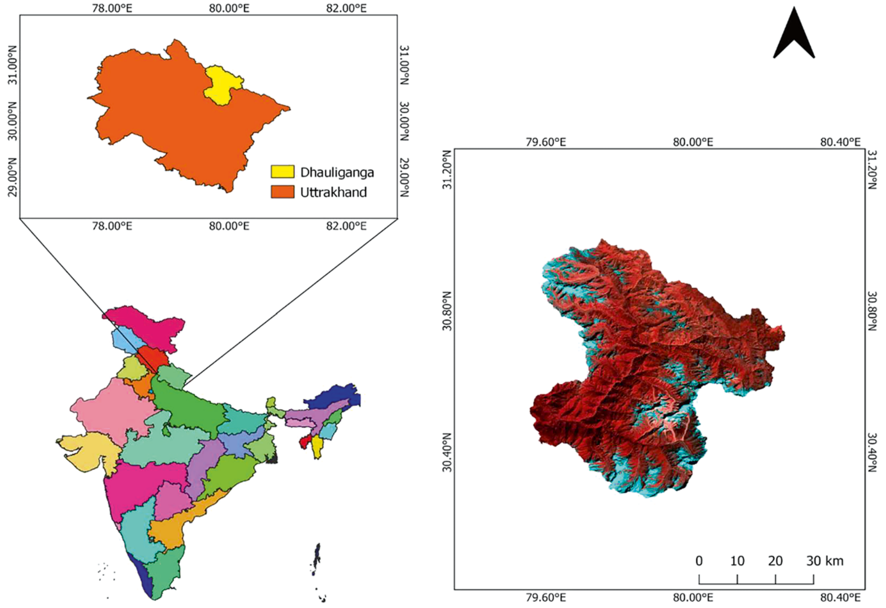

Fig. 3 Study area map

Pindar, Mandakini, and Bhagirathi. At Raini, the Rishi Ganga River joins the Dhauliganga River. At Vishnuprayag, it joins Alaknanda. The Alaknanda Basin has reported a higher rate of melting, retreat rate, and area loss as compared with the Bhagirathi Basin (Bhambri et al., 2011).

4 Results

4.1 Glacier Inventory

A total of 302 glaciers of various sizes and different morphological types are included in the 2020 inventory, which is the base year for inventory; refer to Figs. 4, 5, and 6 for the glacier inventory. The total area covered by glaciers is 555.86 km^2. Large glaciers often contain many compound basins (Refer to Table 3).

Three subclasses are made based on the size. Small, medium, and large for areas less than 1 sq. km, between (1–20) sq. km, and greater than 20 sq. km, respectively. The total area for each subclass is given in Table 4. The number of small glaciers is the largest and the number of large glaciers is the smallest among the three classes; however, the total area of medium-sized glaciers is the maximum among the three. The difference in total area between small glaciers and medium glaciers is much larger (approximately 204 sq. km) than the difference in total area among the medium glaciers themselves. The smallest glaciers are the most numerous among

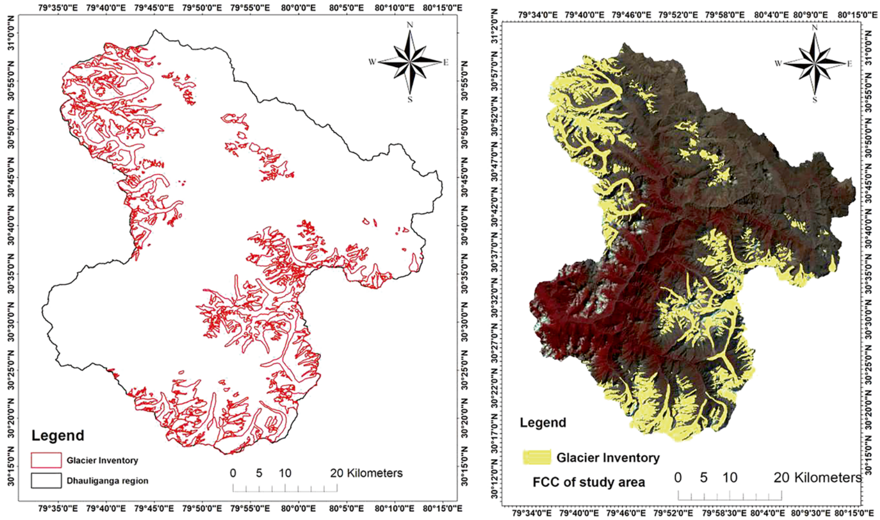

Fig. 4 Glacier inventory of 2000

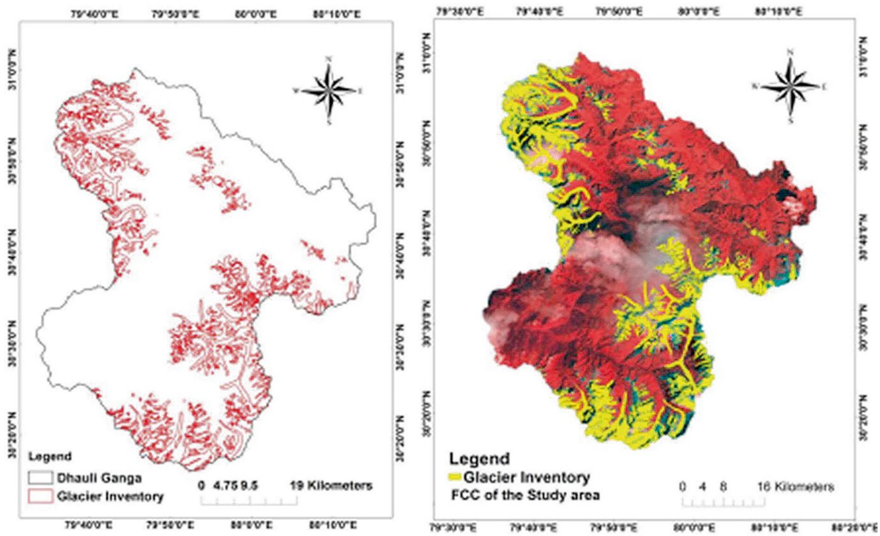

Fig. 5 Glacier inventory of 2013

the three classes, while the large glaciers are the least numerous. However, the total area covered by medium-sized glaciers is the greatest among the three classes.

The number of glaciers, area of glaciers for each class and area occupied by each class are represented in Figs. 7, 8, and 9.

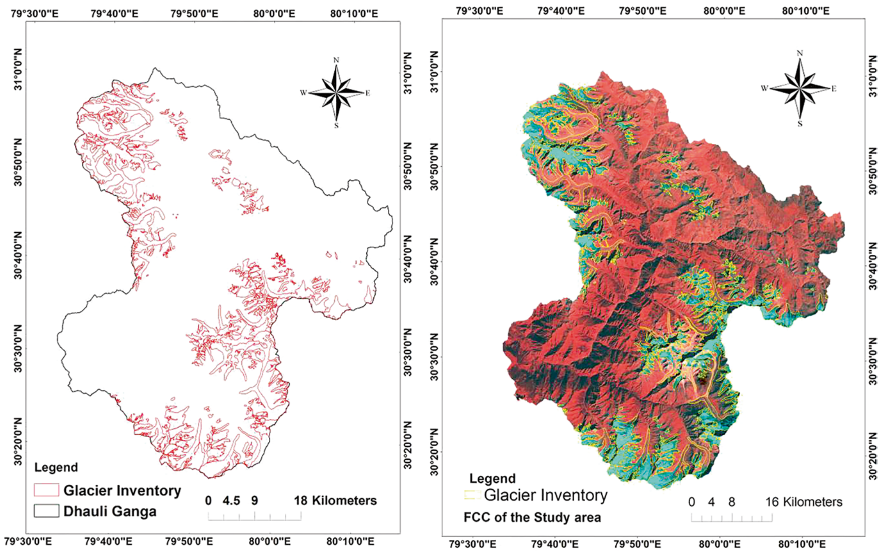

Fig. 6 Glacier inventory of 2020

Table 3 Details about the glacier characteristics

Morphological types	Numbers of glaciers	Area in sq. km	Volume in cubic km
Small/hanging glaciers/permanent snow	220	58.50	1.116
Medium glaciers	76	262.73	1.122
Large glaciers (valley glaciers)	6	234.63	1.142
Total number of glaciers	302		
Total glacierized area		555.86	

4.2 Comparison with GLIMS Glacier Boundaries (2020)

The motive is to modify the glacier boundary and find the differences in extent, size and characteristics between the two inventories.

A comparison is shown with the help of the map given in Figs. 10 and 11.

4.2.1 V-A Scaling Method

The area-volume scaling method is used to calculate the ice volume estimation of glaciers using an empirical equation called the power law relationship (*Reviews of Geophysics - 2014 - Bahr - A Review of Volume-area Scaling of Glaciers. Pdf*, 2015). There are many methods for calculating the volume of glaciers. According to Frey et al. (2014) and *Reviews of Geophysics - 2014 - Bahr - A Review of Volume-area Scaling of Glaciers. Pdf* (2015), area-related scaling approaches have been widely used for estimating ice volume via V-A scaling. Since larger glaciers often

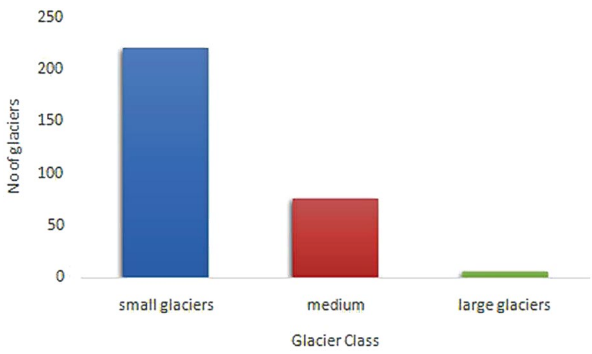

Fig. 7 Number of glaciers per class

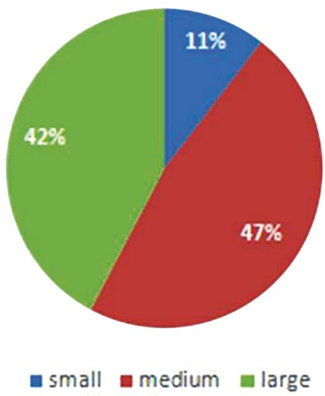

Fig. 8 Area occupied by each class of glacier

Table 4 Comparison of area and volume differences between the new glacier inventory and the GLIMS inventory

	GLIMS	New inventory	Difference
Area of 1 glacier	69.61	62.70	6.91
Volume	65.89	57.16	8.73
Area of 2 glacier	50.62	57.31	−6.69
Volume	42.72	50.59	−7.87

have thicker ice, ice volume is computed as a function of surface area. The V-A scaling relation's standard form is

$$V = CA^{\gamma}$$

where V is the glacier volume, A is the area of the glacier, and C and γ are the scaling parameter and scaling exponent, respectively. Since γ is a constant value for glaciers, it has different values for ice caps, and C is a variable. Here, C and γ are values taken from different studies (Table 5).

We use constant values given by Bahr (1997).

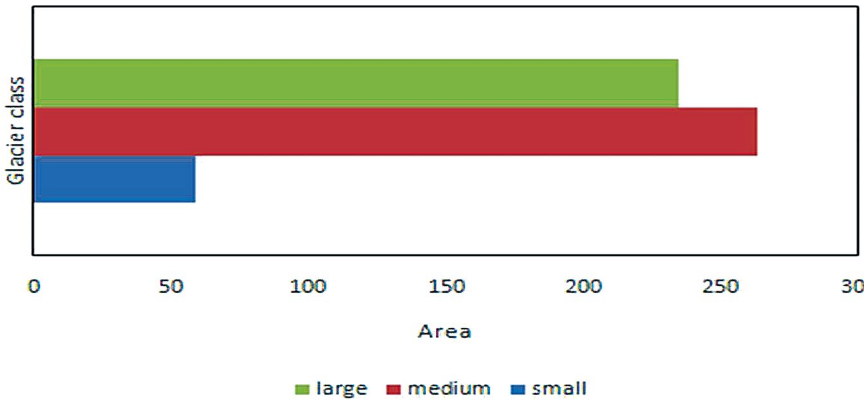

Fig. 9 Areas of glaciers in each class

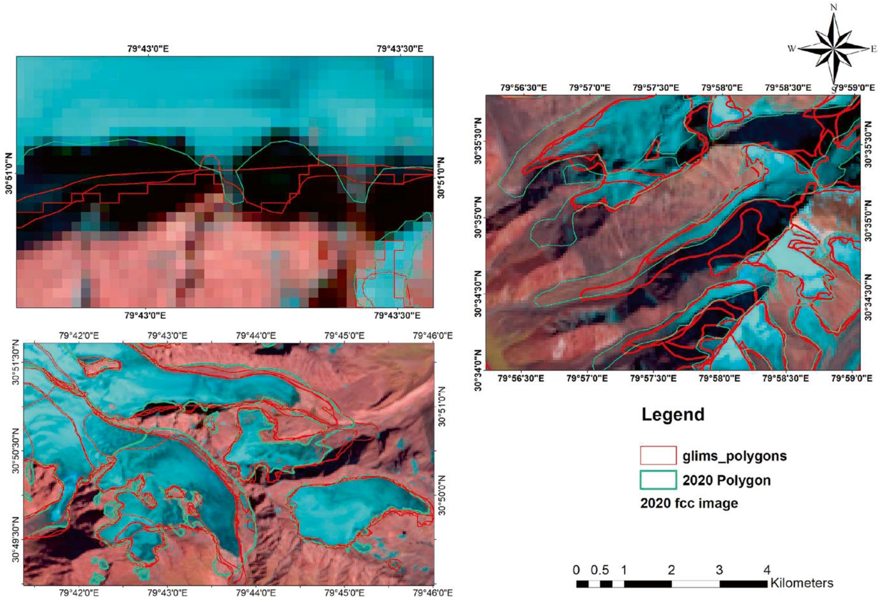

Fig. 10 Comparison with glacier boundaries with GLIMS

4.3 Glacier Retreat and Loss of Area

The total area of the glacier has reduced by 7.49 sq. km for 2000–2013, and for 2013–2020, the value was 3.88 sq. km. Table 6 illustrates that the decrease in area is a clear indication of glacier retreat. The average retreat rate was 4.657 m/year from 2000 to 2013, increasing to 13.236 m/year from 2013 to 2020. If more snow and ice are added to the glacier than are removed by melting, calving, or evaporation, the glacier will advance. If there is a net loss of snow and ice as opposed to a

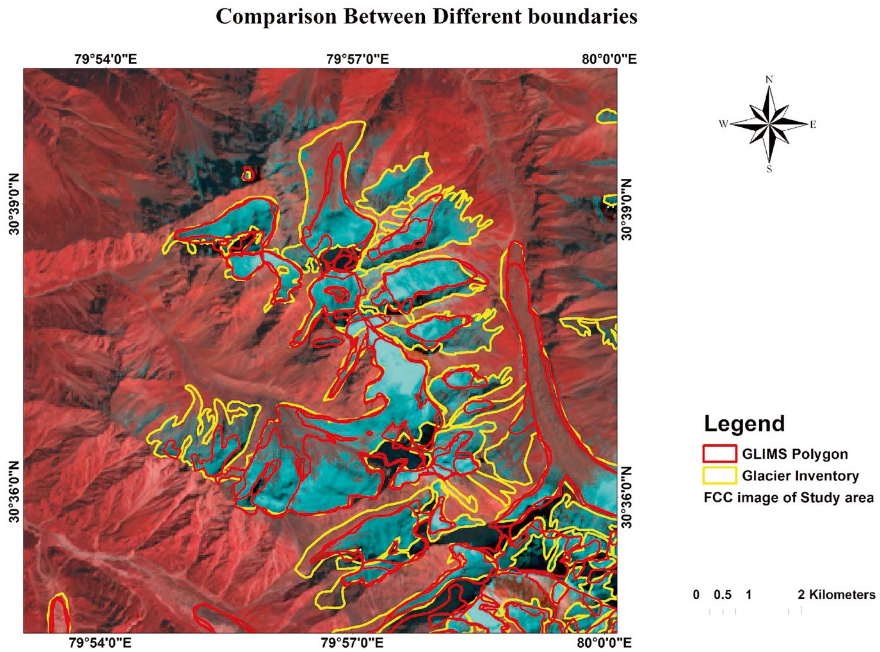

Fig. 11 GLIMS polygon and glacier inventory overlay on fcc image of study area

Fig. 12 Area variability with time

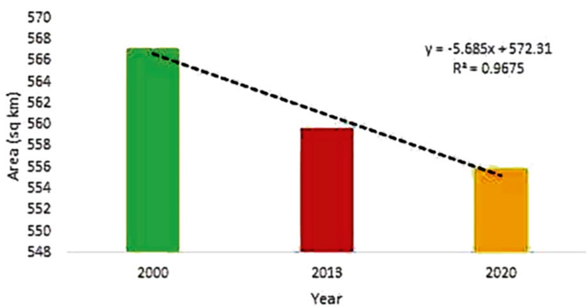

Table 5 Scaling parameter values

C	0.2055
γ (for glaciers)	1.360

Table 6 Total area, volume, and ice thickness of glaciers for 2000, 2013, and 2020. From the table, we can clearly see that there is a linear trend between area and volume

Year	Total area (sq. km)	Volume (cubic km)	Ice thickness (km)
2000	567.23	1.142	2.014
2013	559.74	1.122	2.004
2020	555.86	1.111	1.999

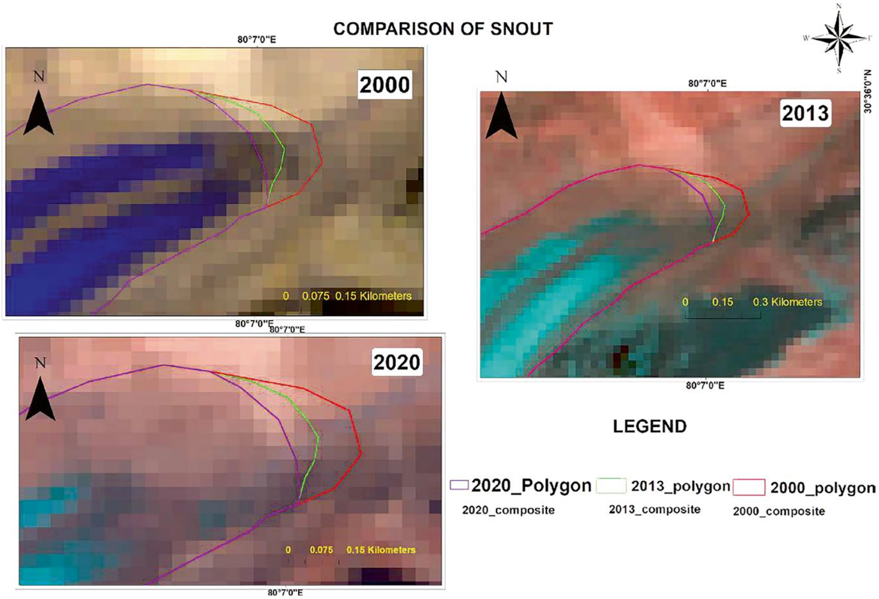

Fig. 13 Glacier snout fluctuations for different periods

Table 7 Areas of glacial lakes

Year	Glacial lake	Area (sq. km)
2000	Vasudhara Tal	0.141
2013	Vasudhara Tal	0.262
2020	Vasudhara Tal	0.513

net gain, glaciers will retreat. Snouts are the termini of glaciers. Until the snout, we can consider a whole glacier from top to snout. From Fig. 12, we can say that the location of the snout shifts. Snout position shifting is an indication of the melting of the glacier. Figure 12 validates the glacier retreat by showing a decline in area with time.

4.4 Glacial Lake

As glaciers continue to retreat and release meltwater, glacial lakes can expand in size and volume, as shown in Table 7 and Fig. 14. As glaciers lose mass and recede due to rising temperatures and changing climate conditions, they release meltwater into depressions, leading to the formation and expansion of glacial lakes. This relationship underscores the dynamic nature of glacier systems and the consequences of climate change in high mountain regions.

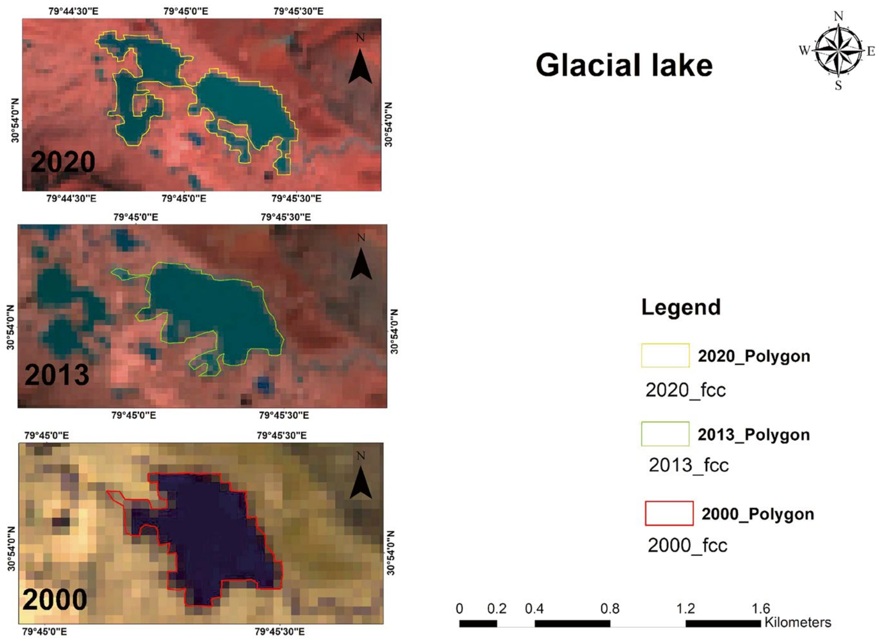

Fig. 14 Glacial lake comparison

4.5 Rise in Temperature

Glacial retreat and the formation of glacial lakes are interconnected with land surface temperature, primarily through their impact on the energy balance and albedo of the region. Over the study period, observations revealed a reduction in glacier area. Additionally, there was an increase in the formation of glacial lakes. These changes collectively indicate a temperature rise and impact mountain ecosystems (Kraaijenbrink et al., 2017; Marzeion et al., 2014). Many studies provide evidence that the Earth's temperature has risen steadily over time (Wang et al., 2023). Over the last three decades, the global surface temperature has increased by 0.2 °C per decade (Hansen et al., 2006), which aligns closely with the warming rate projected in the initial global climate model simulations from the 1980s that accounted for changes in greenhouse gas concentrations (Fig. 15).

5 Discussion

This chapter presents a comprehensive analysis of changes in glaciers over two decades in the Dhauliganga region, which is a part of the Alaknanda Basin in Uttarakhand. To show changes in glaciers, first, we find inventory of glaciers with 2020 as base year. Based on that, digitization is done manually for 2013 and 2000. Furthermore, we make comparisons of glacier boundaries to show changes in

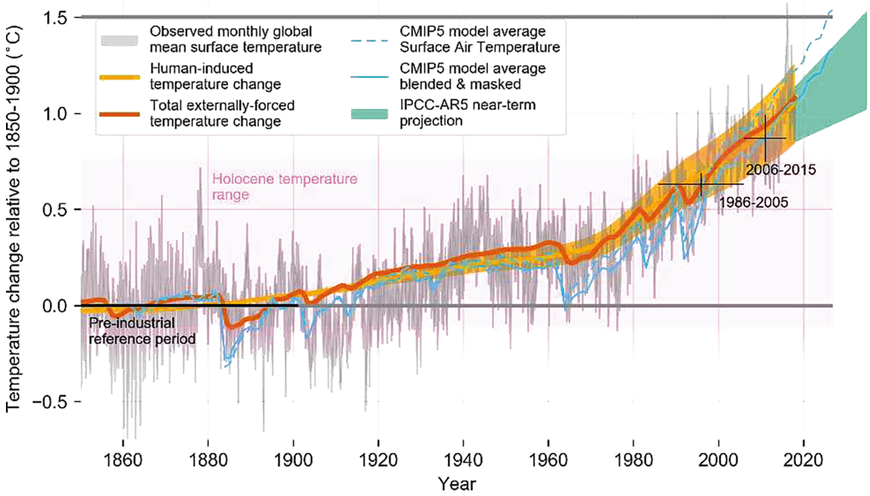

Fig. 15 Global temperature trend. (*Source: IPCC Report (*Change, 2022*)*)

glaciers over two decades. With the MODIS data, we showed a rise in temperature. Since the 1970s, Himalayan glaciers have quickly lost mass, and the rate of loss accelerated after 2000. However, the shrinking is fairly uneven; therefore, it is critical to record individual glacier features and changes in basin size (Mishra et al., 2023). Changes in the glacier mass balance and thinning accelerated melting, which are all signs of climate change. Himalayan glaciers have experienced significant retreat in recent decades, as highlighted by both the Intergovernmental Panel on Climate Change (IPCC, 2007) report and several onsite observations.

By analysing the satellite datasets for the September months of 2000, 2013, and 2020, the following inferences are drawn:

1. The 2020 glacier inventory includes 302 glaciers, totalling 555.86 km^2. They are categorized into small, medium, and large based on size. Medium glaciers cover most of the area, while small glaciers are numerous. The inventory aims to modify glacier boundaries and study changes in extent and characteristics.
2. The total glacier area reduced by 7.49 km^2 from 2000 to 2013 and 3.88 km^2 from 2013 to 2020, indicating glacier retreat. The average retreat rate was 4.657 m/year. (2000–2013) and 13.236 m/year (2013–2020).
3. Glacier retreat and glacial lake expansion are linked to land surface temperature, which affects the energy balance and albedo. Climate change drives glacier mass loss, contributing to glacial lake formation and expansion.

This evidence of a warming climate, i.e. climate change, underscores the need for proactive measures to mitigate potential adverse effects and adapt to the changing environmental conditions in Uttarakhand. Long-term monitoring of glaciers is important because they continually alter their surroundings through the processes of erosion, entrainment, movement, and deposition, and glaciers are among nature's most skilled landscape engineers.

6 Conclusion

The interaction between glaciers and climate is intricate and reciprocal. Glacial ice loss and its withdrawal due to climate change has become a widely investigated subject in various regions worldwide. This is primarily because glacier retreat is often linked to the development and alteration of lakes, particularly glacial lakes, which are frequently observed in these scenarios. There are 302 total glaciers of different types and sizes obtained in 2020 for the Dhauliganga region. Most glaciers are small, less than 1 sq. km in size. The zero-temperature line (also known as the snow line) continues to move upwards as the atmosphere's temperature rises due to global warming. As a result, glaciers experience an increase in liquid precipitation and a decrease in monsoonal solid precipitation. A shift in the snowline will have less impact on the summertime mass balance of the glacier. Therefore, fast glacial retreat and downstream floods will soon be caused by higher atmospheric temperatures and more liquid precipitation at higher altitudes in the Himalayas. If global warming continues, glacial retreat and fragmentation processes will accelerate, which will have a significant impact on the availability of water resources in the Himalayan region. The results of this study improve our knowledge of glacier dynamics in the face of climate change and further the field of glacier research.

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Climate Chaos: Navigating the Dual Challenge Faced by Migrant Workers in Bengaluru, India

Ameena Kidwai, Siji Chacko, and Soumya Tiwari

1 Introduction

Climate change is currently one of the major threats that the world is facing today. This threat is further magnified for Asian countries, which are one of the most vulnerable regions when it comes to climate change-related events (Cecchi, 2023). For instance, the seventh most vulnerable country to climate-related risks under the Global Risk Index is India (Eckstein et al., 2021). Recently, the country has experienced the effects of both slow-onset climate change, like erratic weather and sudden temperature spikes (Sarkar, 2022) as well as an increase in the frequency of disasters such as sudden floods in cities (Sharma, 2021). To mitigate challenges faced due to climate change, socio-economically disadvantaged communities use migration as an adaptive strategy (Rana & Ilina, 2021). Across countries, the number of internal migrants who move as a result of climate-related factors has been difficult to capture. However, some rough estimates and predictions do exist. Recent studies have shown that due to the phenomenon of climate change, 1.2 billion people could be displaced by 2050, 62 million in South Asia alone (IEP, 2020). Another recent estimate of climate migrants in South Asia predicted that by 2050, there would be 40.5 million internal climate migrants (World Bank Group, 2021). Data estimates from 2020 in India have observed that there are 14 million people who migrated as a result of slow-onset changes (Krishnan, 2023). Evidence has also shown that disasters like floods and extreme droughts have forced a significant increase in child labour and child marriages in the country (Bharadwaj et al., 2021a, b, c). As large portions of people migrate to urban areas, with climate change being an important contributing factor, it is important to note that globally, cities are also facing challenges because of climate change. According to an estimation in the World Cities

A. Kidwai · S. Chacko (✉) · S. Tiwari
Migrants Resilience Collaborative, New Delhi, India
e-mail: siji.c@jansahasfoundation.org

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Report (United Nations Habitat, 2022), 43.2% of India's population will be residing in urban areas by 2035. Another estimation by the Government of India suggests that by 2050, 60% of India's population will reside in urban areas (The Mint, 2016). As the population in Indian cities is expected to grow exponentially, experts have argued that these areas will be most affected by floods and heat waves (Kalia, 2022). Sea levels across coastal cities in the country have already risen. It has been estimated that extreme sea level events that previously occurred rarely are expected to happen yearly by the end of the century (IPCC, 2022). Similarly, India's hot summers are also being intensified. Predictions suggest that global warming will be felt more in urban cities in the country (Jainer & Anand, 2021).

Evidently, the impact of climate change may be felt disproportionately in urban areas. Vulnerable populations such as migrants may be affected more intensely. Migrants, with less knowledge of the city's livelihood network and lack of skill, usually live in informal settlements with no access to basic amenities. For example, Delhi's intensified summers have resulted in high fatalities and hospitalisation. The impacts of heatwaves are felt more by the migrant community as they usually live in closely packed, sub-optimal dwellings without amenities such as appropriate housing, ventilation (Hari et al., 2021). Bengaluru is another example of how climate change has severely impacted an Indian city. With rapid urbanisation and improper city planning, the city's Land Surface Temperature has increased by 24% from 1960 to 2017. The city is already experiencing erratic rainfall in some of its regions, and increased land surface temperature (Jayaraman, 2021).

Experts have thus questioned migration as an adaptation strategy for climate migrants, since it is not possible for all migrants to find destinations with liveable environments and services. In many cases, it has been observed that migration has pushed migrants into deeper poverty (Jayaraman, 2021). Therefore, as many destinations face similar threats of climate change, those who migrate due to distress caused by the environment are twice as vulnerable. It has also been argued that over time, countries may not be able to absorb so many migrants in their limited urban cities, and people may be required to move to other countries, which could lead to a global immigration crisis (Basu, 2018).

With the above context, research was undertaken in Bengaluru, Karnataka, to examine climate migration and its consequences on the migrant workers. An attempt has been made to delve into the role of worker protection, encompassing social security and entitlements, along with the concept of safe migration as an adaptive and resilient strategy.

2 Methodology

1. **Secondary Research:** In-depth desk research of existing literature, reports, government plans, policies, policy briefs, climate action plans and government documents on climate change and migration in the region.

2. **Primary Research:**[1] This study used mixed methods, gathering data from 11 migrant community locations/settlements across Bengaluru city, using structured surveys with a sample size of 400 (with only one adult member from a family) and Focus Group Discussions (FGD) conducted in all the communities with a total number of 60 participants participating in the same. The FGDs focused on the challenges faced by migrants because of climate-induced migration. The sample details were as follows:

Sampling Criteria

- The following criteria were used to select sample locations, and it attempted to ensure that the sample was representative:
- Sizeable migrant population in location.
- Sector of work: Community areas were chosen, ensuring diverse occupation sectors such as construction, waste pickers, and domestic workers.
- Type of migrants: Interstate and Intrastate.[2]
- Quantitative survey: The sample was chosen through random sampling in the areas selected.
- Qualitative survey: A sample was chosen from the quantitative survey.

S. no.	Community name	Population size	Sample size from location
1.	Kacherkarnahalli	180–200	20
2.	Borwel Road Community	80–100	10
3.	Attur	120–150	15
4.	Manduru	100–150	15
5.	Kattamanallur	140–160	16
6.	Nagawarapalya	480–500	60
7.	G Ramaiah Layout (Hebbal)	100–110	11
8.	MV Extension (Hoskote)	120–140	14
9.	Rajagopala Nagar	160–180	18
10.	Chwodeshawari Nagara	180–200	21
11.	Kannur 2	170–200	32

[1] The data for the research was collected in September 2023, therefore, many of the questions specifically related to the migrants perception of climate change and monsoon related impacts could consist of a recency bias.

[2] Interstate migrants are individuals or groups of people who move from one state to the other within the country. Intrastate migrants are individuals or groups of people who move within the boundaries of a single state.

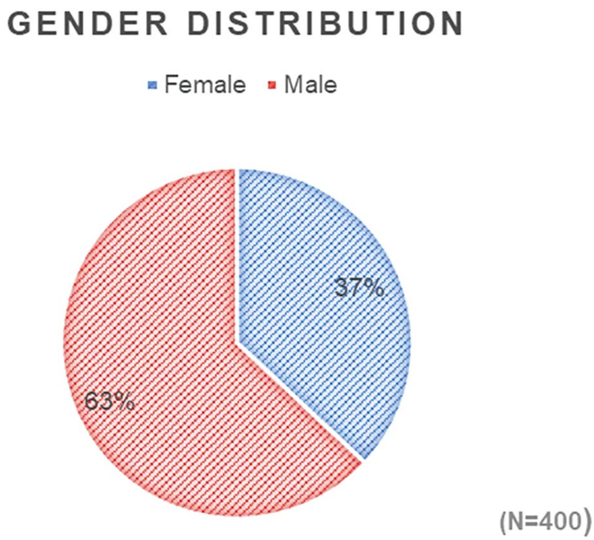


Fig. 1 Gender distribution of sample size. Of the 400 primary respondents, 63% were male and 37% female

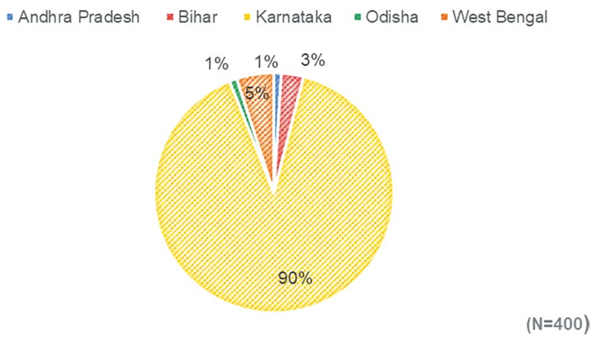


Fig. 2 Source states of respondents. The respondents (90%) were intrastate migrants, mostly from districts such as Yadgir, Raichur, Bellary and Gulbarga and others from Andhra, West Bengal, Odisha and Bihar

2.1 Socio-Demographic Profile of the Sample

Most of the respondents, (69%) were involved in agriculture and allied activities, 24% were involved in construction in the source areas from where they migrated (Figs. 1, 2 and 3).

Of the respondents, 76% were from the construction sector, 7% working as daily wage labourers (Those seeking employment at "nakkas" (various city locations) on a daily basis), 4% were involved in rag picking or dealing with waste and other small numbers belong to other sectors (Fig. 4).

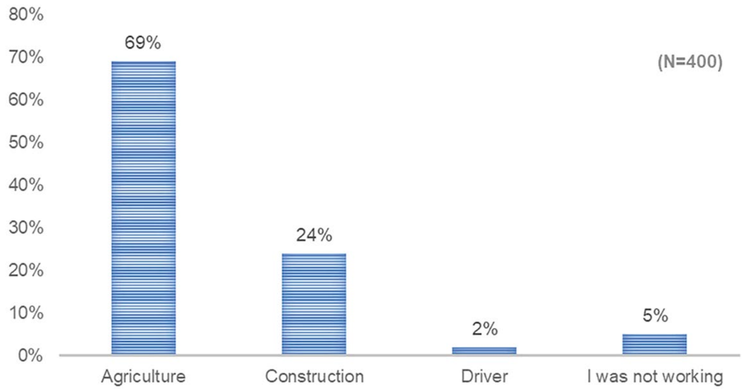


Fig. 3 Occupation of respondents in source areas

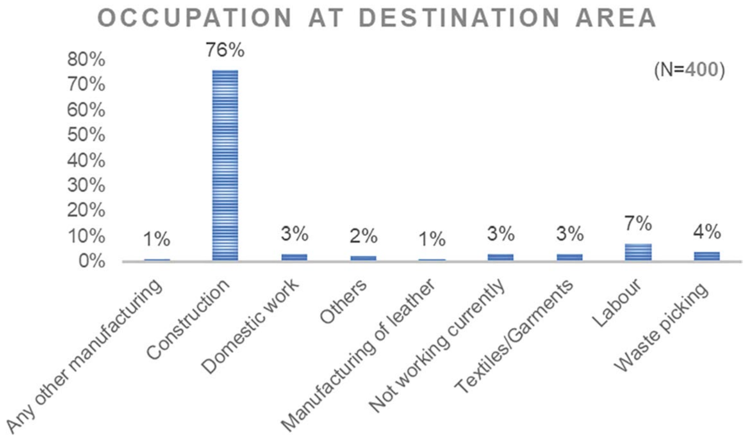


Fig. 4 Occupation of respondents at destination area

2.2 Migration Related Details of Respondents

Of the respondents, 53% returned to their destination once a year and 26% mentioned that they returned twice a year to their source locations for various reasons (Fig. 5).

Almost all the respondents, 89% migrated only to one destination, Bangalore for the last 1 year (Figs. 6 and 7).

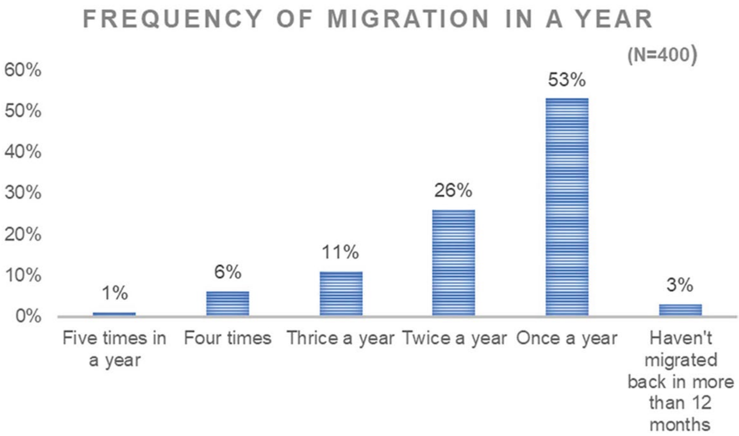
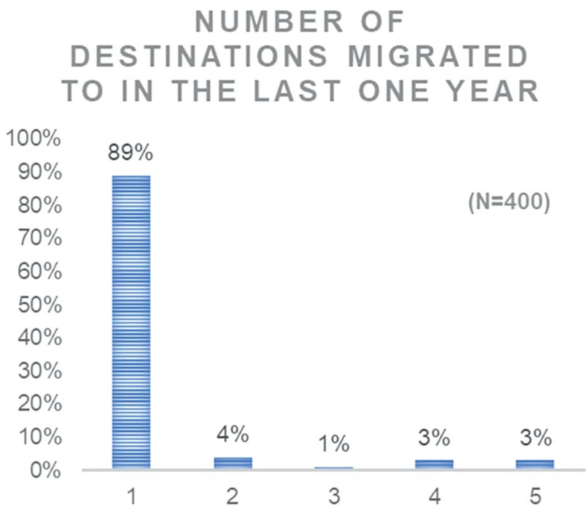


Fig. 5 Distribution of frequency of migration in a year

Fig. 6 Distribution of the number of destinations respondents migrated to in the last 1 year



3 Results and Discussion

A recent survey found that out of the 20 most climate-at-risk locations in the world, 13 were reported in India (Nichols, 2021). With increasing temperatures, rise in sea levels and erratic rainfall patterns, climate change was experienced in both rural and urban areas. The results and discussion section focused on three parts to understand the climate-induced distress migration that households face. In the first part, we focused on the situation at source locations where repeated crop failures and loss of livelihood as a result of changing weather conditions were increasingly driving migration. In the second part, we attempted to understand the current impact on destination locations of climate change with migration being increasingly adopted

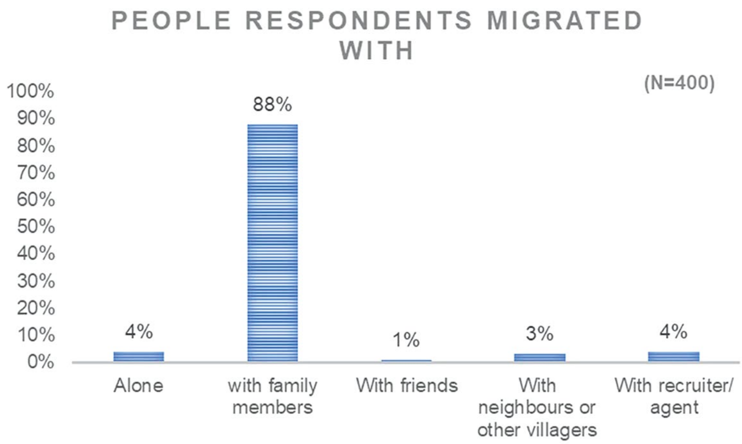
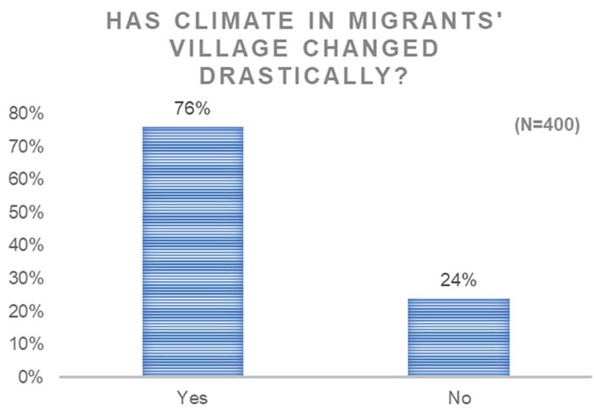


Fig. 7 Distribution of categories of people respondents migrated with

Fig. 8 Perception of migrants about climate change in village



as a coping mechanism, specifically in Bengaluru, Karnataka. In the third part, we focused on understanding potential resilience systems which may be incorporated by different stakeholders to reduce or mitigate climate migration related distress.

3.1 Migration: A Response to Distress at Source Locations

According to the Census (Government of India, 2011), there were 144.3 million agricultural labourers in India. CMIE's Consumer Pyramid Household Survey suggested that over the past 3 years, an additional 11 million workers have joined the agricultural workforce (*The Economic Times*, 2022). Therefore, given that a sizable proportion of the population was still dependent on agriculture, it remained a vital sector of the Indian economy. In India, as in many developing countries, a significant portion of this sector is oriented toward self-sufficiency and relies on rainfall for irrigation (IOM, 2019). However, slow-onset changes, such as increasing heat and erratic rainfall patterns, have led to challenges like recurrent crop failures or low crop production (Leads Connect, 2023).

Research has shown that Indian farmers have witnessed drastic impacts of climate change over the years in the form of high temperatures and erratic rainfalls (Datta et al., 2022). This observation aligns with the primary survey findings, as 76% of the respondents (Fig. 8) mentioned that they witnessed a significant change in climate in their source locations. Of these, a majority witnessed this change in the form of rainfall patterns and temperature. Seventy-six percent of the respondents stated that rainfall had decreased, while 92% responded that the temperature had increased over the past few years. In addition, migrant workers also mentioned the deeper effects of climate change they were facing.

> *The weather has changed a lot in our village in the past few years. There is no proper rainfall during the rainy season, more heat in summer, drought conditions. We are not able to work in summer season because of more heat. Compared to the early days as the days went by, we felt more sweat while working in the field.*—Suresh, Erstwhile Agriculture Worker

The change in weather conditions has had numerous impacts on the working conditions of those living in rural areas. Lack of job availability, stagnant wage rates and loss of working hours are some of such impacts in the agriculture sector. According to existing data, 34 million jobs will be lost in India by 2030 because of heat waves, with rural areas being the most affected (Gupta, 2022). This prediction is in line with the results from the survey which shows that 46% respondents had to migrate because of lack of availability of jobs in their villages. Out of these, almost 50% of respondents belonged to the agriculture sector.

> *There was no rain, no crops, no job, and low wage. For the first time we were experiencing such a situation in our village. I had taken a loan for my daughter's marriage, and it was getting difficult to pay back the loan. Hence, I decided to move to Bengaluru in search of work.*—Gayathri, Agriculture Worker

Evidence suggested that as heat and humidity levels rise, work which was required to be done outdoors—agriculture and construction remained significantly affected and led to labour loss worldwide. In India, outdoor workers are already dealing with this situation which has led to a loss of labour. Research conducted by Nature Communications found India has lost 101 billion hours per year of work because of heat exposure (Parsons et al., 2021).

> *In the summer season in my village, nobody comes out. Many old people died in the village due to heat in the summers. People cannot go to work because of the heat. So, we borrow money but are unable to repay it and end up accumulating high interest.*—Belaku, Agriculture Worker

Moreover, temperature rise also led to erratic rainfall patterns, a cause of concern for those working in the agriculture sector as farming was highly dependent upon timely rainfall. In our primary research, 74% of respondents perceived that the rainfall pattern in their source areas has decreased, leading to low crop production, further aggravating their existing precarity with lack of jobs, food insecurity, indebtedness, or financial loss.

> *Sometimes there is no rain because of which there are no crops. Other times there are excess rain because of which our crops get ruined and get submerged in water.*—Ramnath, Agriculture Worker

One of the strategies adopted by workers in rural areas to combat distress was migration. Therefore, climate migration, especially in the case of slow-onset changes, was closely interlinked with those who migrated due to economic distress. As change in weather conditions led to low production of crops or repeated crop failures, it ultimately led to lesser working hours, stagnant wages, low demand for labour and food insecurity. This created a situation of extreme economic distress for rural workers. Often leading to distressed workers migrating as a coping mechanism.

According to our primary research, a little less than half (46%) of the respondents (Fig. 10) said that their reason for migration was a lack of job availability in rural areas. For climate-related factors which influenced their migration, 42% of the respondents (Fig. 9) said that they decided to migrate owing to rising temperatures, which meant that due to drought-related conditions, they had to leave their locations. The data suggests that extreme drought (42%) and crop failure (14%) would have resulted in loss of livelihood (26%). Additionally, 78% of respondents mentioned that similar conditions in their village drove their neighbours and family members to migrate (Fig. 10).

> *Around 60% to 70% of families in my village have gone to other places for work. Their reasons are like ours. There is no rain, heat has increased, there is a lack of food for us.*—Kiran, Agriculture Worker

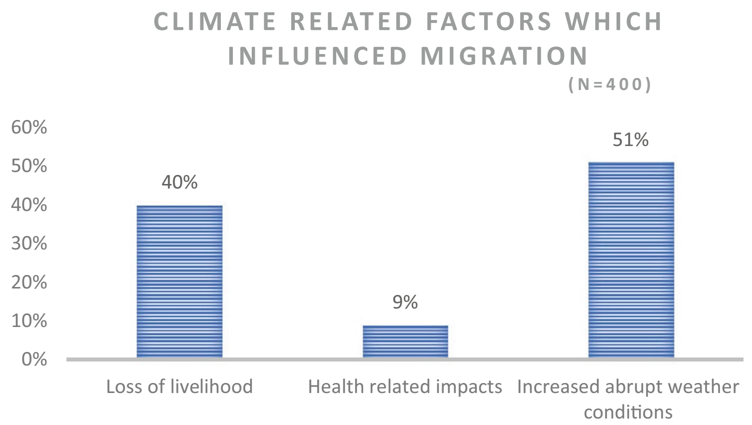


Fig. 9 Climate-related factors that influenced decision to migrate

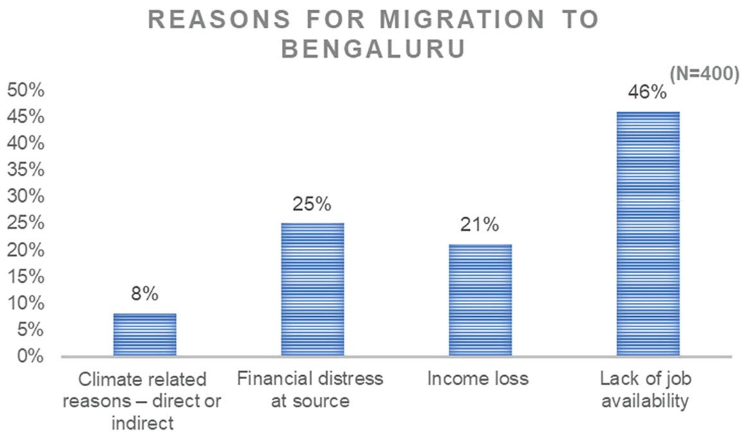


Fig. 10 Reasons for migration to Bengaluru

We observed that climate change will continue to impact rural populations. This was particularly true for those working in the agricultural sector, such as smallholding farmers and agricultural labourers in India, who already lived in precarious conditions. They suffered extreme distress due to changing weather conditions, which led to the potential loss of jobs and livelihood. This distress was also likely to led to an increase in migration as an adaptive strategy, putting increasing pressure on destination areas (Bharadwaj et al., 2021a, b, c).

3.2 Navigating Through the Challenges at Destination Locations

For decades, reasons for migration have focused on socio-economic factors and better job opportunities in India's major destination hubs, ignoring the considerable impact on the already deteriorating living and working conditions for migrants across destination cities due to climate change (Hari et al., 2021). Experts suggest migrant's existing vulnerability has further increased at destination locations because of the rise in the frequency of climatic events such as heatwaves and floods.

Bengaluru city in Karnataka exists as a major destination hub for migrants. According to the Census 2011, 44.3 lakh individuals inhabiting the city were classified as migrants, i.e., over 50% of the population (The Times of India, 2019). Even though the city has contributed to significant development of the state, this growth has also led to pressure on its environment. The city faces increasing temperatures, decline in or erratic rainfall. For example, in the past few years, the news on floods and their increasing intensity has been a yearly occurrence (Chu & Michael, 2018). Furthermore, a vulnerability assessment of the city in 2016 found that 91% of the area in Bengaluru was facing a high degree of vulnerability because of climate change (Basu, 2016).

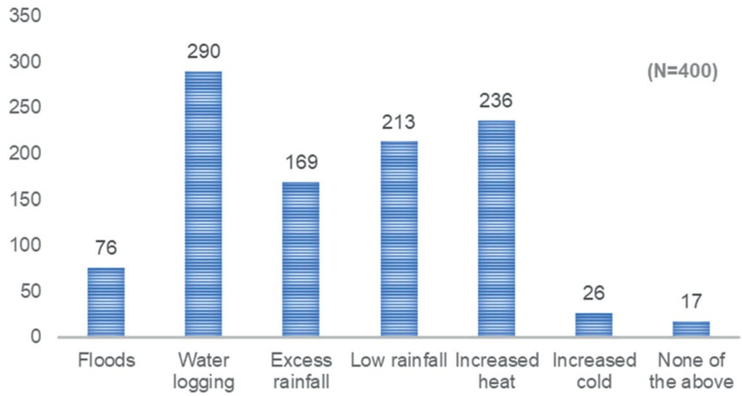


Fig. 11 Climate impacts in Bengaluru

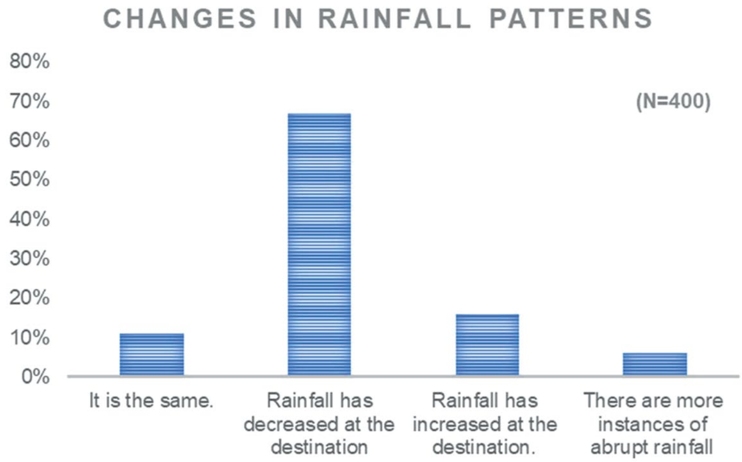


Fig. 12 Changes in rainfall patterns as perceived by respondents

> *When we came to Bengaluru about 12 years back, there were only bushes and cemeteries in this area. The weather was cool all the time and there was frequent rainfall. We had cleared up space and set up our home here. Quickly, we saw tall buildings being constructed all around us. Now the area is congested, and the weather has become hotter, and we experience lesser rainfalls in the city.*—Venkateshwar, driver

During primary research with migrants, it was observed that they were experiencing or had experienced varied climatic impacts. Overall, 97% of the respondents mentioned that they had faced some form of climate change-related impacts since their migration to the city. Most common impacts included water logging, erratic or low rainfall and increased heat in the city (Fig. 11). It was also observed that 23% i.e., 56 out of the 243 respondents mentioned that they were faced with both water-logging and flood situations in the city.

Water logging is a common issue in our area. When there is heavy rain, rainwater enters our tent, and we are unable to sleep the whole night. We keep our children in the saree and tie them to the ceiling to keep them up above the flood water. We cannot go to work for one or two weeks. Here we cannot ask anyone for a loan or money to look after our daily needs, we do not have any savings. If you go and ask anybody…they say, 'why have you come here, go to your village.' We can't survive here when it rains heavily, we are helpless.—Rajmathi, construction worker

Our primary research findings have been largely in line with recent reports on changing weather conditions in Bengaluru. For example, a news report observed till August 2023, the rainfall deficit in Bengaluru Urban district was 17% and 20% in Bengaluru rural (H.S., 2023). Furthermore, according to the India Meteorological Department (IMD), Bengaluru recorded a shortfall of around 90% of expected rainfall (Kaggere, 2023). Similarly, in the survey, 67% of the respondents stated that rainfall patterns had seen a decline in the city since they migrated (Fig. 12).

As rainfall patterns continued to decline, in the same month, the city came tantalisingly close to breaking a 124-year-old record for the hottest August day (Kaggere, 2023). In the survey, 85% of respondents mentioned the heat intensity had increased during the summer months (Fig. 13). It is important to note that with 76% of the respondents involved in construction, 7% in daily labour and 4% in waste picking and processing, most of the respondents would be directly affected by the extreme heat conditions due to exposure.

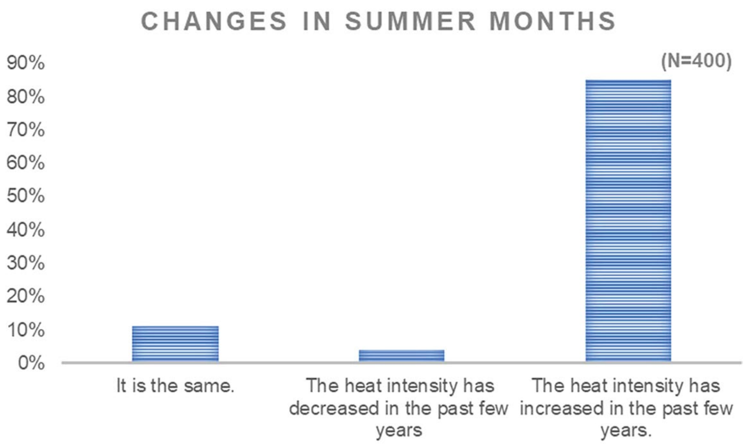


Fig. 13 Changes in summer months as perceived by respondents

3.3 Climate-Induced Vulnerabilities and Impeded Quality of Life

In this section, we focus on climate migrants' existing vulnerability being impacted because of the nature of their work and the conditions they live in at destination locations.

3.3.1 Working Conditions

The Periodic Labour Force Survey of India found that 232 million workers are engaged in outdoor wage work—having the lowest incomes and difficult working conditions (Government of India, 2023). With climate change-related events becoming more frequent, these workers continue to remain the most vulnerable.

A report showed that 380 million people in India, or 75% of the labour force, are exposed to heat-related stress. It also predicts that as a consequence of climate change, construction work could become too risky for workers by 2030 (McKinsey, 2020). In Indian cities, outdoor work, such as construction work, is mostly taken up by migrant workers. Our primary research showed that 74% of respondents were impacted by the intensity of heat at their work location in the city. Rising temperatures affect their health, which further results in loss of workdays and wages.

A study analysed the impact of heat on migrants from South India and found that 77% of workers reported heat-related illnesses such as headache, nausea and vomiting. Women reported that a combination of heat stress and lack of access to proper toilets led to Urinary Tract Infections (UTI) and kidney-related illnesses (Venugopal et al., 2016).

3.3.2 Living Conditions

In the mega cities of India, migrant workers continue to live in extremely deplorable conditions with inadequate access to basic amenities such as electricity, sanitation and drinking water (Jane, 2016). In the survey, migrants mentioned that the dwellings they lived in lacked access to basic amenities—81% lacked proper drinking water, 90% to sanitation facilities, 85% to electricity and 92% to proper drainage systems in their area (Figs. 5, 6 and 7).

> *During summer we sleep out at nights and always face risks of snake bites, insects and mosquitoes. We do not get much support from outsiders; we have to support ourselves.*— Bhuwaneshwari, construction worker

It is found, the areas which house migrants in big cities are more vulnerable and susceptible to climate-related impacts and larger climatic events (Venugopal et al., 2016). For example, during the 2018 Kerala floods, it was observed that migrants lived in areas more prone to floods, landslides, etc. These settlement areas were generally more unhygienic, which could potentially lead to epidemics such as waterborne diseases (Rajan et al., 2022). Similarly, in our sample, 51% of migrant workers (n = 202) mentioned that they had faced some form of impact on their living conditions owing to climate change in Bengaluru (Fig. 8). Out of these, 168 respondents faced lack of proper sanitation, which led to health-related impacts. For at least 122 migrant workers, during the period of a climatic event, their living area became completely uninhabitable (Fig. 9).

> *Last year in September, there was heavy rain in Bangalore and lakes overflowed. Water flooded the community and all our clothes, beds, food grains, and firewood got washed away in the flood.*—Geetha, domestic worker

3.3.3 Building Resilience and Adaptive Systems for Safer Migration

Labour migration is a multifaceted phenomenon, influenced by socio-economic and environmental determinants, including climate change. Empirical data suggests that climate change adversely affects agrarian livelihoods, as evidenced by 69% of the surveyed respondents engaged in agriculture and related activities. They reported substantial climate-induced repercussions, such as decreased agricultural yield and limited alternative income sources in their native villages. Consequently, migration emerged as a crucial adaptive mechanism, particularly for those relocating to Bengaluru.

In this study, most of the migrants (90%) were intrastate migrants, mostly from districts such as Yadgir, Gulbarga and Raichur. Data reveals that these districts have some of the backward/most backward Talukas—Bellary having 12 backward Talukas, 11 in Gulbarga and 6 in both Yadgir and Raichur. Of these districts Yadgir,[3] Raichur,[4] and Gulbarga[5] are also classified as aspirational districts in India (FKCCI, n.d.). In terms of HDI and literacy rate, these are among the most backward districts in Karnataka. Therefore, these migrants come from extremely backward communities. Once they reach destinations, a lack of limited resources forces them to live in deplorable conditions. For example, it is to be noted that 85% of the families live either in shanties or temporary housing with tarpaulin or corrugated sheets. This increases their exposure and their vulnerabilities, although almost 21% of them have been in Bangalore for more than 10 years. In such cases, it is essential to

[3]Yadgir district has a sizable population of vulnerable populations such as Scheduled Castes/Scheduled Tribes of the state. The district's economy is primarily agrarian and its inhabitants are faced with extreme poverty and lack of livelihood opportunities, therefore, making seasonal migration for work a common occurrence.

[4]Raichur has been one of the aspirational districts in India with low socio-economic indicators. The weather of the area is almost dry throughout the year as this district comes under the north-eastern dry zone area. While gold mines are famous, the people depend mostly on agriculture depending on rain. The district is very high on poverty and comparatively backward in infrastructure and development.

[5]Gulbarga is an adjacent district of Yadgir with a substantial population of minority communities. Agriculture is the primary livelihood for the people of Gulbarga. The district was covered under the Backward Regions Grant Fund (BRGF) that was initiated in 2007. The district is known for the cultivation of crops like sorghum (jowar), pulses, sunflower, groundnuts, and red gram (tur dal). Being a district dependent on rains for cultivation, in July 2023, the farmers in the districts were protesting to declare Gulbarga as a drought hit district, demanding compensation for the loss of crops and waiving off the farmers loans.

understand even with climate change-related impacts at destination—how migrants can be made resilient to climate distress.

Evidence suggested that social protection programmes can make development more inclusive and sustainable. They end up playing an important role in supporting individuals and households from marginalised communities. Therefore, even in situations of climate crises where migrant households are usually worst affected due to their precarity, social protection can play a key role in supporting them (Schwan & Yu, 2018).

Social protection plays a key role in climate resilience efforts by reducing the vulnerability of individuals forced to migrate due to climate change, as well as for the communities at their destination locations due to their exposure to climate risks. Thus, it becomes important that access to social security is ensured to the optimum at both—source and destination locations. At the source locations, programmes focused on food security, employment/livelihood programmes, weather insurance and crop failure insurance could be beneficial for individuals in distress. The strengthening of existing social safety nets such as Public Distribution System (PDS), "MGNREGA," Jal Jeevan Mission, NRLM, Integrated Watershed Management Programme (IWMP), Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), National Mission for Sustainable Agriculture (NMSA), Ayushman Bharat, PM Suraksha Yojana, Sambal, *Ladli Behaha*, National Crop insurance programme (NCIP), Rashtriya Krishi Vikas Yojana, Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), National Mission for Sustainable Agriculture (NMSA) and Integrated Child Development Services (ICDS), could provide households the means to cope and remain resilient during periods of climate and economic shocks at source locations. Similarly, for migrants at destination, ensuring the portability of these existing schemes such as MGNREGA and ICDS and monitoring effective portability under "One Nation One Ration Card," Ayushman Bharat and Building and Other Construction Work cards could be beneficial in supporting during the initial migration phase. Affordable and safe housing would also help them combat climate change impacts at destination as well as supporting them with post arrival training to enable safe migration could be found beneficial. However, it must be noted that even though entitlement benefits from social security schemes could help economically support migrants initially, it is essential to focus on long-term action plans and preparedness by governments for climate change. Policies for climate migrants should ensure to address the need for better working conditions, affordable housing and access to basic amenities such as water, electricity and sanitation (Bharadwaj et al., 2021a, b, c).

In the current scenario, some policies and national action plans exist to address climate change-related impacts and risks in the country. The Government of India has taken these steps through the National Action Plan on Climate Change. This plan recognises the role of states and local governments in combating climate change at the ground level and has directed states to set up action plans that align with the National Action Plan (Government of India, 2021). Similarly, The Karnataka State Action Plan on Climate Change focuses on 31 priority areas with a deeper focus on vulnerable sectors. As per the plan, the state government is required to set up conservation mechanisms to meet the growing need for water in urban areas. It further discusses the need to conduct studies to augment water resources from flood water (Government of Karnataka, 2011). Bengaluru is also in the process of formulating a City Action Plan for Climate Change. The Action Plan focuses on mitigation and adaptation to climate change. While mitigation would focus more on Greenhouse Gases (GHG) emissions, adaptation focuses on specific actions that are necessary to build resilience of the vulnerable communities. It provides a climate lens to the overall sectoral plans of the city.

It is imperative that the Action Plan also addresses the needs of migrant workers in the city and formulates strategies to overcome the consequences of heat stress and flooding on the living and working conditions of migrant workers. According to our primary research, 85% of the migrants responded that they did not feel that the government is adequately addressing climate change and its impacts. The City Action Plan is a good opportunity for the government to address the growing vulnerability of migrant workers in Bengaluru.

4 Conclusion

Climate change is an undeniable reality that the world is currently facing. Countries such as India are particularly vulnerable to the risks associated with climate change. Factors such as lack of sufficient livelihood opportunities, disillusionment with farming and allied jobs, and less income from agriculture and farming, directly or indirectly, are linked to increasing the vulnerability of marginalised households. Climate change has further intensified these challenges for the most vulnerable communities. Erratic rainfall patterns and rising temperatures have made agricultural work increasingly difficult, resulting in economic distress, job scarcity and stagnant wages.

To address these challenges, many rural workers turn to migration as a coping strategy, seeking opportunities in urban areas. These workers often reside in informal settlements, lacking proper infrastructure and government support. Numerous research studies have shown that the impacts of climate change and urbanisation disproportionately affect vulnerable communities, such as migrant workers, thereby exacerbating inequalities. Consequently, climate migrants encounter additional challenges in cities like Bengaluru, where rising temperatures and erratic rainfall patterns are prevalent.

Access to social protection schemes represents one avenue to mitigate the challenges faced by climate migrants. These schemes ensure that development is more inclusive for vulnerable communities by providing access to jobs, ration and healthcare. However, while social protection schemes are crucial, it is important to note that they primarily address the economic development of vulnerable communities. Thus, enhancing the delivery of social protection programmes at the source and destination locations could help reduce climate-induced distress migration and would act as a resilience-building measure. For a more comprehensive approach, there is an urgent need to revise or implement National Action Plans, State Action

Plans, and City Action Plans in a way that places the most vulnerable communities and their respective sectors at the forefront.

Often climate mitigation-related planning is of a top-down approach, without including the voices of the affected community. Thus, for more inclusive policies, it is essential that moving forward, a bottom-up and inclusive approach where the community has a say in the climate action plans.

With each passing day, the impacts of climate change are worsening, underscoring the necessity of protecting India's most vulnerable communities. Efficient and inclusive policies must be formulated and implemented before we reach a point where the challenges posed by climate change become insurmountable.

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Effects of Algal Biodiesel–Petro-diesel Blends in Emission from IC Engine

Rachan Karmakar, Anita Rajor, Krishnendu Kundu, Narpinder Singh, Rajesh Kumar, Pavan Gangwar, Savita, Vrince Vimal, Bhaskerpratap Chaudhary, Sanjoy Gorai, Pradeep Kumar, Pratibha Naithani, Suman Naithani, Rachna Sharma, Neeraj Kumar, Sourish Bhattacharya, and Aoujasva Veer Vikram Singh

R. Karmakar (✉) · P. Kumar · P. Naithani
Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India
e-mail: rachan.in.air@gmail.com

A. Rajor
School of Energy and Environment, Thapar Institute of Engineering and Technology, Patiala, India

K. Kundu
Department of Biofuel, CSIR CMERI CoEFM, Ludhiana, India

N. Singh
Department of Food Science and Technology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

R. Kumar
Department of Chemistry, S.S.J. University, Campus Almora, Almora, India

P. Gangwar
Department of Electronics and Communication Engineering, IMS Engineering College, Ghaziabad, India

Savita · V. Vimal
Graphic Era Hill University, Dehradun, India

B. Chaudhary
Chandigarh Group of Colleges, Chandigarh, India

S. Gorai
Thapar Institute of Engineering and Technology, Patiala, India

S. Naithani
Department of Environment, Graphic Era (Deemed to be University), Dehradun, India

R. Sharma · N. Kumar
Roorkee Institute of Technology, Roorkee, India

S. Bhattacharya
CSIR CSMCRI, Bhavnagar, India

A. V. V. Singh
University of Delhi, Delhi, India

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1 Introduction

Due to the general lack of awareness regarding the exact availability of non-renewable fossil fuels and their relatively affordable cost, the widespread utilization of biofuels remains limited. Additionally, the high market price (Amano-Boadu et al., 2014; Roychowdhury et al., 2011) of conventional oils poses a significant barrier to the popularity of biofuels. However, considering the projected depletion of fossil fuels within the next century (Shafiee & Topal, 2009) and the expected 50% increase in liquid fuel consumption after 2030 (B.P. Energy Outlook 2030, 2011), it becomes highly advisable to explore fuels derived from renewable bioresources. While biodiesels present compatibility with existing diesel engines, boasting high thermal efficiency and affordability, their full utilization (B100) in engines has faced challenges due to certain properties like viscosity and density.

The environmental impact of greenhouse gas emissions from petro-diesel is well-documented, causing severe pollution (Smith et al., 1993; Riahi et al., 2011) and contributing to global warming (Hoel & Kverndokk, 1996; Steinberg, 1999). Therefore, the decision to use algal biodiesel as a reference biofuel in this experiment is supported by the fact that fuels derived from algae can sequester approximately 0.6% of carbon dioxide (Ponnusamy et al., 2014). Notably, carbon dioxide serves as a growth stimulant for algae (Holbrook et al., 2014; Dassey et al., 2014; Widjaja et al., 2009), making algal biodiesel a favorable choice. The rapid growth rate of algae and its minimal land area requirement further solidify the rationale behind selecting algal biodiesel for this experiment (Chisti, 2007; Dauta et al., 1990).

2 Materials and Methods

The primary source of algal biomass was from ponds designated for pisciculture within the Punjab Agricultural University campus in Punjab, India. These ponds are utilized for year-round experiments and the cultivation of commercial fishes. During the winter season, these ponds undergo a cleaning process, often experiencing significant algal bloom. To prepare the ponds, the excess algae are removed and discarded. Additionally, samples of algae were gathered from the Simlapuri Nahar (canal) in Ludhiana, Punjab. These specific algae were selected for the experiment due to their economic insignificance, easy accessibility, and lack of utilization for any specific purpose. Collection of the algae was performed using standard algae nets, and subsequently, these specimens were brought to the laboratory for the drying process.

2.1 Production of Algal Biodiesel

Algae sourced from the pisciculture ponds were transported to CSIR MERI CoEFM in Ludhiana, India, and stored within laboratory ponds. Under optimized conditions, the cultivated algae were sun-dried for a duration determined by prevailing atmospheric temperature and humidity (Karmakar et al., 2018a).

For algal oil extraction, a solvent extraction method was employed with the use of *n*-hexane and the Soxhlet apparatus (Matthäus, 2011). The resulting algae oil extracted from the sun-dried algae was utilized for biodiesel production through the process of transesterification. Due to the notably high free fatty acid content (FFA) of the algal oil, a two-step biodiesel production process was implemented (Pandey et al., 2013). Initially, the FFA was reduced using an acid-catalyzed reaction involving sulphuric acid (H_2SO_4) with a 7:1 molar ratio, 1.5% catalyst concentration, 55 °C reaction temperature, 90 min reaction time, and 180 min settling time (Karmakar et al., 2019, n.d.). Subsequently, an alkali-catalyzed reaction was carried out utilizing potassium hydroxide (KOH) as the catalyst where a molar ratio of 6:1, catalyst concentration of 3%, 60 °C of reaction temperature, 60 min of reaction time, and 150 min of settling time were used (Karmakar et al., 2019, n.d.). These reactions were conducted within a water bath shaker (see Fig. 1) (Kumar et al., 2017), where the oil underwent a reaction with methanol (Ragit et al., 2013) to produce algal fatty acid methyl ester (FAME), also known as algal biodiesel (B100).

2.2 Preparation of Algal Biodiesel–Petro-diesel Blends

Three blends (B10, B20, B30) of algal biodiesel were prepared with petro-diesel. B10 was prepared by mixing 100 mL of algal biodiesel (B100) with 900 mL of petro-diesel. B20 was prepared by mixing 200 mL of algal B100 in 800 mL of petro-diesel, and B30 was prepared by adding 300 mL of B100 to 700 mL of petro-diesel. All these algal biodiesel blends were used in an engine to examine their emission characterization.

Fig. 1 AVL 244 di-gas analyzer for detection of emission from algal biodiesel–petro-diesel blends

2.3 Emission Characterization of Algal Biodiesel

All the algal biodiesel petro-diesel blends prepared were utilized alongside petro-diesel to operate a compression ignition (CI) engine, as outlined in Table 1. The engine was installed inside the workshop of the mechanical engineering department, whereas the outlet of the engine was kept outside the workshop for the measurement of emission of fuels.

Emissions from the engine's exhaust were examined using a di-gas analyzer (AVL 444) (Fig. 1). The analyzer's probe was inserted into the exhaust to measure quantities of CO, CO_2, NO_x, unburned hydrocarbons (HC), and exhaust temperature (measured using a thermometer) across various engine loads (0, 20, 40, 60, 80, 100, and 120 kg) for the use of B10, B20 and B30 algal biodiesel and petro-diesel.

3 Result and Discussion

3.1 Emission of Carbon Monoxide

Studies suggested that an increase in engine load decreased the fuel-to-air ratio within the engine, which enhanced fuel combustion and reduced CO production. Biodiesel, containing inherent oxygen, tends to undergo more thorough combustion compared to petro-diesel, resulting in lower CO emissions. This experiment revealed a gradual decrease in CO emissions with increased engine load, notably indicating significantly lower CO emissions from algal biodiesel B10 (ranging from 80 to 530 ppm), B20 (ranging from 71 to 510 ppm), and B30 (ranging from 63 to 492 ppm) in comparison to petro-diesel (ranging from 102 to 563 ppm) (Fig. 2). This trend aligns with similar studies conducted on biodiesel derived from waste cooking oil (An et al., 2012).

Table 1 Details of the CI engine used for emission characterization of algal biodiesel petro-diesel blends

Maker	Kirloskar
Model	AV1
Rated brake power, bhp/kW	5/3.73
Rated speed, rpm	1500
Number of cylinder	1
Bore X stroke, mm	80 × 110
Displacement, cc	552.920
Compression ratio	16.5:1
Cooling system	Water cooled
Lubrication system	Forced feed
Standard injection timing	27° BTDC

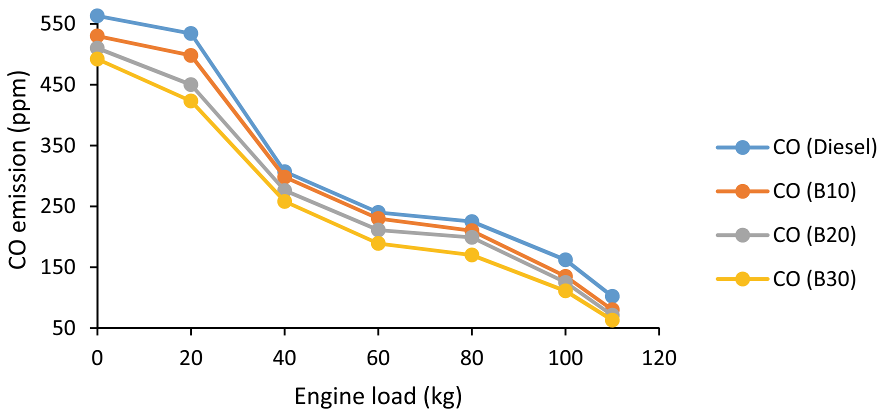

Fig. 2 Emission of CO for the combustion of B10, B20, B30, and petro-diesel

3.2 Emission of Carbon Dioxide

In compression ignition (CI) engines, a more air-rich mixture was introduced into the combustion chamber with increased engine load. Consequently, improved fuel combustion occured in CI engines under higher load conditions, resulting in a notable change in emission patterns. Specifically, the emission of carbon dioxide (CO_2) exhibited an inverse relationship with carbon monoxide (CO) emission; CO_2 emission tends to escalate as engine load increases.

During experimentation, a consistent rise in CO_2 emission was observed for all the blends of B10, B20, B30, and petro-diesel. For algal biodiesel blends' combustion, the lowest CO_2 emission was recorded under zero load conditions (2.9% for B10, 2.9% for B20, 2.8% for B30, and 3.1% for petro-diesel, respectively), while the peak emission occurred during overload condition in both diesel (4.3%) and algal biodiesel (3.4% for B10, 3.3% for B20 and 3.3% for B30, respectively) scenarios (refer to Fig. 3). However, across all engine load conditions, biodiesel consistently emitted lower CO_2 compared to diesel. This phenomenon can be attributed to biodiesel's lower carbon-to-hydrogen ratio in comparison to diesel, resulting in higher CO_2 emissions from the latter (Xue et al., 2011).

3.3 Emission of Oxides of Nitrogen

At higher engine loads, the combustion chamber generated increased heat, leading to a rapid rise in NO_x emissions (Raheman & Ghadge, 2007; Zhu et al., 2010). In our current experimental setup, NO_x emissions were observed to escalate with engine load during combustion of both diesel and biodiesel (see Fig. 4). Particularly noteworthy was the higher emission observed in algal biodiesel blends, which increased from 23 to 170 ppm for B10, 25 to 189 ppm for B20 and 27 to 201 ppm for B30 compared to petro-diesel, which increased from 22 to 161 ppm from lowest

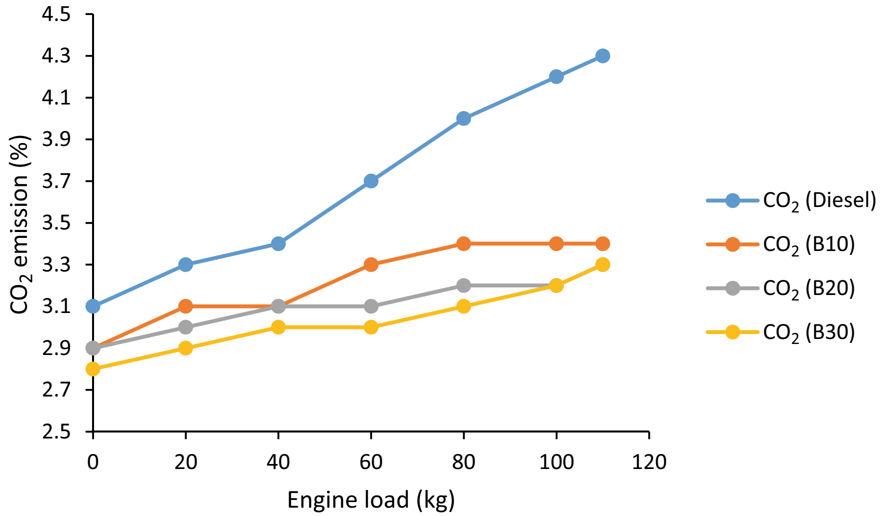

Fig. 3 Emission of CO_2 for the combustion of B10, B20, B30, and petro-diesel

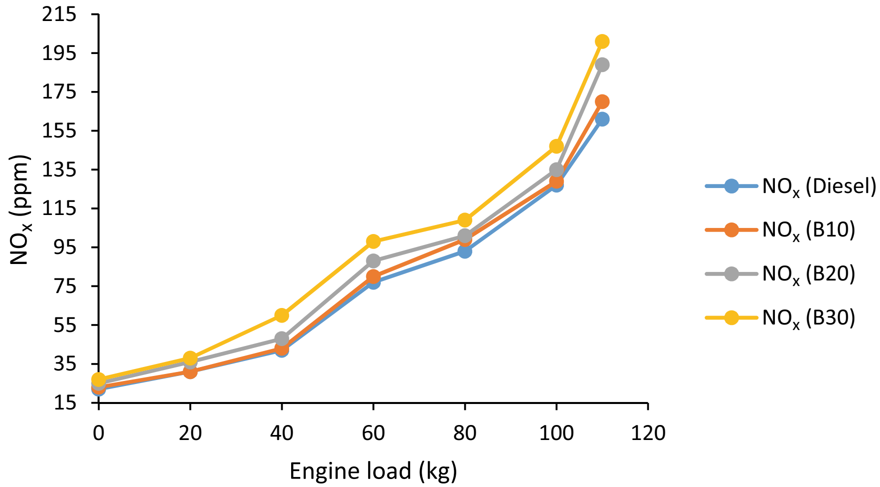

Fig. 4 Emission of NO_x for the combustion of B10, B20, B30, and petro-diesel

to highest and overload engine load conditions. This disparity could be attributed to the inherent oxygen content in biodiesel, which potentially enhanced nitrogen oxide formation. Additionally, the higher exhaust temperature generated during biodiesel combustion (as depicted in Fig. 6) suggested elevated cylinder temperatures. Consequently, it was reasonable to infer that algal biodiesel combustion yielded higher cylinder temperatures, thereby producing more NO_x compared to petro-diesel combustion. Strategies to mitigate NO_x emissions from algal biodiesel could involve the inclusion of beneficial additives (Palash et al., 2014) or the implementation of a catalytic converter (Zukerman et al., 2009) or a de-NO_x catalyzer (Madia et al., 2002) within the CI engine's exhaust manifold.

3.4 Emission of Unburned Hydrocarbon

Incomplete combustion within the engine leads to the emission of unburned hydrocarbons (HC). Due to the inherent oxygen content, biodiesel tends to facilitate better combustion, theoretically resulting in lower HC emissions compared to petro-diesel. In our observations, across various load conditions (refer to Fig. 5), algal biodiesel consistently exhibited lower HC emissions than conventional diesel. Specifically, diesel HC emissions decreased from 40 to 27 ppm with increasing engine load. B10 had a decrease from 37 to 21 ppm, whereas emission of B20 tailed off from 37 to 18 ppm from 0 kg load to 120 kg load. In contrast, algal biodiesel blend B30 showed an initial rise from 30 ppm at 0 kg load, peaking at 31 ppm at 20 and 40 kg load, and gradually decreasing thereafter up to overload conditions. Shirneshan's report in 2013 also noted a similar trend, citing higher HC emissions at 40 kg load during the combustion of waste frying oil methyl ester, followed by a gradual decrease with increasing load (Shirneshan, 2013). This may be attributed to the higher density of biodiesel, resulting in larger fuel droplet sizes during atomization, impeding complete combustion, and leading to increased HC emissions. However, as the engine load increases, a richer air-fuel mixture, containing more air, and inherent oxygen in biodiesel, fosters improved combustion, thereby reducing the emission of unburned HC (Karmakar et al., 2018b, 2020, 2023).

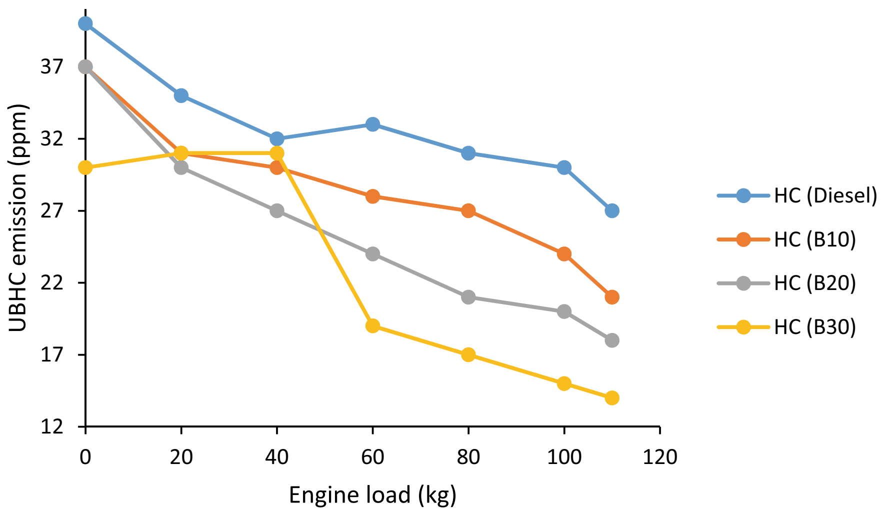

Fig. 5 Emission of HC for the combustion of B10, B20, B30, and petro-diesel

3.5 Temperature in the Exhaust

The exhaust temperature holds significance, as any elevation in it can impact the surrounding environment's temperature, potentially affecting the local flora and fauna. Moreover, it serves as an indicator of the internal engine temperature, a crucial factor influencing various gas emissions. Within our study, we observed higher exhaust temperatures during algal biodiesel blends' combustion compared to diesel (as depicted in Fig. 6). In both cases, temperatures exhibited a rapid increase (from 41.1 to 59.5 °C for diesel and 41.1–61.2 °C for B10, 42.3–63.2 °C for B20 and 45.1–66 °C for B30) with escalating engine load.

4 Conclusion

The consistent supply of diesel or alternative fuels has gained significant importance owing to widespread industrialization and urban growth globally. Concerns regarding the depletion of crude petroleum underline the potential scarcity of this fuel in the future, consequently driving up the market price of petro-diesel. Utilizing biodiesel derived from untapped algae could serve as a viable solution, considering the lack of commercial value for the raw material. Despite the notably high free fatty acid (FFA) content in the algae oil produced in this experiment, a two-step process allows for the production of biodiesel meeting ASTM standards in all aspects. It is anticipated that no modifications to the engine would be necessary if a diesel-biodiesel blend (with a lower percentage of biodiesel) is utilized. Further investigation is required for the application of pure biodiesel (B100) in CI engines, particularly focusing on engine component compatibility. The high calorific value of this biodiesel suggests potential for generating higher engine power while consuming less fuel. Notably, while combustion of this biodiesel results in higher NO_x emissions compared to diesel, other

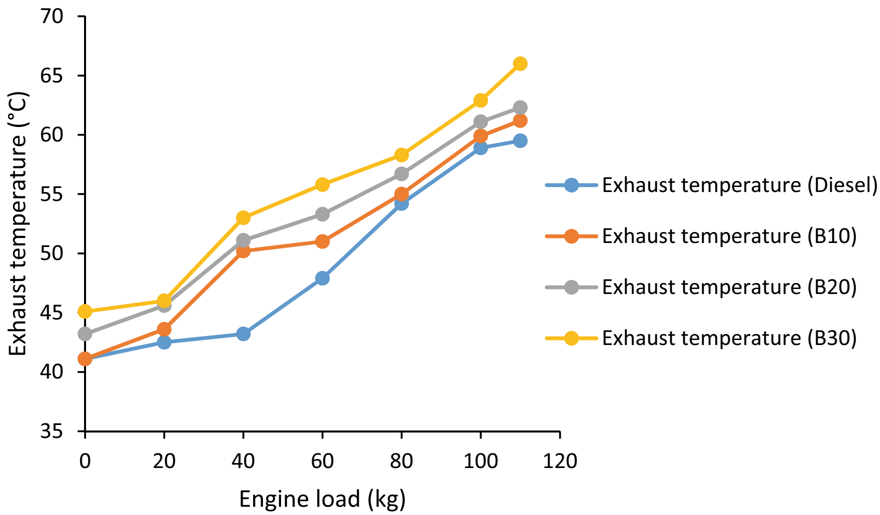

Fig. 6 Exhaust temperature for the combustion of B10, B20, B30, and petro-diesel

gas emissions such as CO, CO_2, and unburned hydrocarbons could potentially be significantly reduced if this biodiesel is used as an alternative to petro-diesel.Contribution of AuthorsRachan Karmakar: Formulation and application of research; Anita Rajor: Research supervisor; Krishnendu Kundu: Research supervisor; Narpinder Singh: Research guide; Rajesh Kumar: Co-researcher; Pavan Gangwar: Co-researcher; Savita: Literature review; Vrince Vimal: Rectification of the paper; Bhaskerpratap Chaudhary: Literature review; Sanjoy Gorai: Co-researcher; Pradeep Kumar: Rectification of the paper; Pratibha Naithani: Rectification of the paper; Suman Naithani: Writing of the paper; Rachna Sharma: Proof reading; Neeraj Kumar: Documentation of research; Sourish Bhattacharya: Providing research facility; Aoujasva Veer Vikram Singh: Documentation.

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Mitigating Drought Stress in Various Grain Crops: Strategies for Alleviation

Sonal Aggarwal, Akanksha Negi, Riya Barthwal, Deepika Kathuria, and Narpinder Singh

1 Introduction

By 2025, projections indicate a global population increase of 9.7 billion, with approximately 65% of people depending primarily on agriculture for their livelihoods. In developing nations, this reliance is expected to soar even higher, reaching around 90% (Castaneda et al., 2016). Consequently, a nation's economy and food supply will be heavily dependent on agriculture. However, agriculture faces a multitude of challenges, including various biotic and abiotic stressors. Abiotic stress factors encompass conditions like metal toxicity, drought, temperature alterations, high soil salinity and oxidative stress, all of which can cause lasting harm to plants, leading to restricted growth, disrupted metabolism, lower yield, and even genetic mutations in offspring (Bhat et al., 2020). During 2015–2016, cereal productivity plummeted by roughly 50% compared to typical years, posing a severe threat to food security. Additionally, climate change has exacerbated this issue with erratic rainfall patterns, rising temperatures, and the spread of flood and drought-prone areas, all of which have negatively impacted soil quality and crop growth. Despite debates surrounding the influence of elevated CO_2 levels on crop yields, Gray et al. (2016) reported that increased CO_2 concentrations fail to offset the detrimental effects of drought on both photosynthesis and yield. Various studies highlight the adverse impact of elevated temperatures and water stress on crop yields. Singh et al. (2008) also documented fluctuations in both starch and protein levels in various wheat cultivars due to water stress at different stages of grain development.

S. Aggarwal · A. Negi · R. Barthwal · D. Kathuria · N. Singh (✉)
Department of Food Science and Technology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India
e-mail: vicechancellor@geu.ac.in; narpinders@yahoo.com

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Additionally, in Canada, extreme events and droughts in the early 2000s and 2010–2011 led to crop yield reductions of up to 50% (Wheaton et al., 2008) In the United States, annual major disasters causing over a billion dollars in damages have led to agricultural losses surpassing $220 billion when drought and heat events were combined (NCEI, 2020).

Drought and heat significantly harm crop productivity, affecting molecular, physiological, morphological, biochemical, and ecological aspects. This results in substantial yield and income reductions for farmers. For example, maize and wheat may see up to a 40% yield decrease with a 40% reduction in water availability (Daryanto et al., 2016). Cowpea, a vital African crop, experiences yield reductions ranging from 34% to 68% depending on the timing of Drought stress (DS) (Farooq et al., 2017). Deryng et al. (2014) have contributed significantly to understanding climate change impacts on crops, especially in the context of heat stress and elevated CO_2 levels. With global warming, it is crucial to assess heat stress effects and develop strategies for enhanced heat tolerance. Given climate change's diverse impacts on crop production, exploring adaptive measures to mitigate heat and drought effects is essential. To meet rising global food demand, urgent research and practices promoting drought-tolerant plants and sustainable agriculture methods are necessary.

2 Cause of Drought Stress in Plants

Plants, integral to ecosystems, face diverse challenges in their life cycles. Drought, a major factor affecting agricultural production, particularly impacts staple crops like wheat, rice, and maize, making them susceptible to yield and quality loss. The study of drought-resistant mechanisms is crucial to mitigate the predicted 30% increase in yield loss. Factors such as reduced rainfall, soil salt accumulation, temperature shifts, and intense light contribute to drought stress. In some cases, apparent droughts result from factors like soil characteristics (e.g., salinity, cold temperatures, flooding), limiting root water absorption, leading to physiological drought or pseudo-drought (Arbona et al., 2013). The climate simulation models predict an impending increase in DS due to climate change. Drought significantly impacts normal plant growth, water retention, and water usage efficiency, affecting physiological, biochemical, morphological, and molecular properties (Fathi & Tari, 2016). Water stress diminishes a plant's ability to regenerate ribulose 1,5-bisphosphate, photosystem II (PS-II) efficiency, stomatal conductance, light saturation rate, and decarboxylation velocity. Categorized by water availability, water stress occurs as either water logging or water deficit, both major contributors to global agricultural production losses. Water shortages, intensified by high temperatures and human activities, result in drought conditions, further stressing plants (Wan et al., 2017).

2.1 Global Warming

The fast industrialization and modern technologies have both had a negative impact on the ecosystem's balanced climate. Prolonged temperature rise leads to soil moisture loss, intensifying greenhouse gas occurrence and global warming. Climate change significantly impacts crucial crops like rice, wheat, and maize due to low precipitation and flooding, leading to substantial output losses. Global warming induces instability in natural cycles, causing increased temperatures, as observed in the 2003 European drought, resulting in a 30% decline in net production in both Western and Eastern Europe (Ciais et al., 2005). Despite some climate change effects being potentially advantageous, such as increased CO_2 promoting higher photosynthesis rates, the overall impact includes decreased yearly precipitation in numerous rain-fed agricultural areas worldwide (Warner & Afifi, 2014).

2.2 Rainfall Anomalies

Unlike areas supplied by canals and rivers, regions reliant solely on rainfall for crop production are anticipated to face increased stress. In rainfall-dependent areas, drought episodes are closely linked to annual rainfall distribution, with specific years posing a higher likelihood of water stress (Konapala et al., 2020). Low rainfall leads to diminished soil water levels, causing reduced water potential in leaves and stems, resulting in water deficit stress. Continued trends suggest a projected 70% reduction in summer precipitation in rain-fed areas by the start of the twenty-second century (Yu et al., 2013). During water scarcity, plants adapt by maximizing water absorption through root growth while minimizing transpiration to conserve water. Additionally, anthropogenic activities, particularly climate change, industrialization, deforestation, and urbanization, significantly alter rainfall patterns, affecting water availability to plants (Fatima et al., 2020).

3 Effect of Drought Stress on Plants

Plants face various stresses due to changing environmental conditions and respond to survive through metabolic changes and gene expressions. Drought stress (DS) occurs with a significant decrease in soil moisture, high temperatures, and low humidity, resulting from an imbalance between evapotranspiration and water intake from the soil (Lipiec et al., 2013). In dry environments, plants adapt by expanding roots to access more water and minimizing stomatal water loss when transpiration exceeds water uptake. DS is characterized by reduced leaf water potential, stomatal closure, and diminished cell growth (Farooq et al., 2009), leading to symptoms like leaf rolling, wilting, yellowing, and scorching. Heat stress is a sustained increase in soil and air temperatures beyond a critical threshold, causing permanent damage to plant growth. It induces changes in leaf structure, yielding thinner leaves with a larger area (Poorter et al., 2009). Morphological changes are further influenced by alterations in leaf anatomy, with leaves developing under water deficit conditions having smaller cells and higher stomatal density (Shahinnia et al., 2016). Combining drought and heat stress is more damaging than individual occurrences. Water scarcity and soil salinity trigger oxidative, osmotic, and thermal stresses, negatively impacting plant growth (Landi et al., 2017). The link between drought and heat stress is evident; reduced stomatal conductance and transpiration in water-deficient conditions can lead to heat stress with elevated leaf temperatures (Król, 2013). In tropical regions, the simultaneous presence of water deficit and high temperatures can swiftly impair plant growth (Zandalinas et al., 2017). Moreover, drought stress affects various physiological and biochemical processes in plants, including photosynthesis, chlorophyll production, nutrient metabolism, ion uptake, translocation, respiration, and carbohydrate metabolism (Farooq et al., 2009; Li et al., 2011).

Drought significantly hampered cell growth by lessening turgor pressure. Severe water scarcity disrupted water flow to neighbouring cells via the xylem, thereby hindering processes like mitosis, cell elongation, and expansion. Consequently, this led to diminished plant height, leaf area, and overall crop growth (Kaya et al., 2006). Barley, when subjected to drought stress, experiences adverse effects on individual grain weight, tiller count, spike count, and grains per plant, resulting in decreased grain yield. Furthermore, drought stress restricted germination by impeding water absorption and reduced seedling establishment (Kaya et al., 2006).

DS significantly impacts nutrient uptake, transfer, and metabolism in plants (Farooq et al., 2009). Under drought, both root nutrient uptake and translocation to shoots decrease. Drought affects energy availability for nutrient assimilation, particularly for nitrogen, phosphorus, potassium, and sulfur, requiring energy-dependent processes for plant growth. Alongside macronutrients, drought-induced deficiencies in certain micronutrients like manganese, iron, and molybdenum, which became more accessible in non-drought environments due to increased solubility and reduction (Hu & Schmidhalter, 2005). Various plant species exhibit reduced absorption and translocation of macronutrients (N, P, and K) in response to drought. DS impacts cation active transport and membrane permeability (K^+, Ca^{2+}, and Mg^{2+}), reducing root cation absorption (Farooq et al., 2009). Enzyme activities related to nutrient digestion and assimilation are restricted by DS. Water deficiency alters gene expression, upregulating some genes and downregulating others (Jain & Chattopadhyay, 2010). DS modifies the expression of genes linked to dehydrin/late embryogenesis abundant (LEA) proteins and molecular chaperones, which safeguard cells from protein denaturation (Mittler & Blumwald, 2015). Abscisic acid (ABA), produced in roots under DS, transfers to shoots, causing stomatal closure and reduced plant growth. Elevated ABA levels regulate gene expression in drought-response, including dehydrin genes (DHN 1/RAB and DHN 2) and glycine-rich protein genes (Rorat, 2006). DS disrupts the balance between reactive oxygen species (ROS) generation and the antioxidant defence system in plants. This stress can result in the overproduction of ROS, especially superoxide ($O_2^{\bullet-}$) and hydrogen peroxide (H_2O_2), causing oxidative stress by damaging cell membranes, nucleic acids, proteins, etc. (Schieber and Chandel, 2014). Excess ROS can lead to physiological and biochemical disorders, affecting cellular macromolecules like

DNA. However, plants have evolved efficient antioxidative defines systems to regulate ROS overproduction and mitigate oxidative damage. The balance between ROS production and detoxification is associated with a plant's tolerance to abiotic stresses. DS not only affects plant growth and productivity but also impairs nutrient uptake behaviours, influencing plant-nutrient relationships. Temperature variations influence soil physio-chemical and microbial processes, impacting nutrient availability for plants. The combination of drought and heat stress poses additional challenges, affecting plant growth and nutrient absorption. Ideal soil moisture levels are crucial for optimal plant growth, with deviations above or below the threshold negatively impacting grain quality and production. Conversely, insufficient water availability in the rhizosphere hampers plant growth and inhibits nutrient uptake (Chadha et al. 2019). This issue is expected to become more severe due to global warming and climate variability.

4 Plant Responses to Drought Stress

In anticipation of challenging dry and drought conditions, plants employ specific mechanisms to maintain their physiological and metabolic processes, evolving adaptive strategies to impede the detrimental repercussions of drought. They undergo changes in their transcriptome, proteome, and metabolome, modifying cellular and physiological functions to establish cellular equilibrium (Seleiman et al., 2021). Plants activate defence mechanisms and respond to DS to enhance water use efficiency, limiting water loss by transpiration and other means. These responses fall into broad categories of escape, avoidance and tolerance mechanisms. Triggered by stress-inducing stimuli, such as disruptions in cell equilibrium or challenges in water absorption, plants modify cell membranes to maintain turgidity and prevent water loss (Nardino et al., 2022). Signal perception is facilitated by smaller molecules like diacylglycerol and phosphatidic acids, serving as secondary messengers that transmit stress signals before the actual signal transduction process begins. This results in various response mechanisms, helping plants adapt and survive in DS.

4.1 Drought Escape Response Mechanism

Drought escape (DE) is a crucial plant adaptation strategy involving accelerated development and reproduction to ensure survival before an impending drought. During favourable conditions, plants swiftly transition from their vegetative to the flowering phase, aiming to produce seeds before the onset of drought halts their life cycle. DE leads to a heightened metabolic rate, promoting cell expansion and division. Open stomata and elevated rates of gas exchange enable efficient photosynthesis and respiration but with low water utilization efficiency (WUE), facilitating excessive plant development (Kooyers, 2015). In *Arabidopsis thaliana*, this strategy optimizes water use for growth and selection during drought, favouring early flowering. Mild drought during early vegetative stages prompts plants to swiftly transition to a more efficient drought tolerance mechanism. In contrast, during flowering and grain-filling stages (terminal drought), plants adopt a growth acceleration strategy, expediting their life cycle to set seeds before severe drought conditions intensify (Kottmann et al., 2016).

4.1.1 Early Flowering Response

Plants often display precocious flowering, initiating at a smaller size or younger age, enabling earlier seed production and reducing dehydration risk during vulnerable stages like flowering and grain filling. Early flowering facilitates a swift transition from vegetative to reproductive phases, a strategy adopted by 'short-season' or 'short-cycle' genotypes to effectively evade drought (Shavrukov et al., 2017). The lentil cultivar PAR exemplifies a successful drought escape with its early flowering and shorter life cycle, thriving in dry spring conditions and achieving high grain yield and harvest index (Sánchez-Gómez et al., 2019). Pearl millet, in contrast, possesses advantageous traits such as early flowering, prolific tillering, a deep root system, and efficient water use, collectively contributing to its ability to thrive under challenging drought conditions (Merga, 2020).

4.1.2 Short Vegetative Phase/Early Maturity Response

Plants that escape drought conditions tend to invest fewer resources in their vegetative growth and prioritize the development of reproductive structures, such as flowers and seeds to increase grain yield directly. This strategic shift leads to a shorter duration of the vegetative phase and an earlier attainment of maturity. A brief vegetative phase, occurring before the onset of drought, leads to a decrease in plant biomass because there is less time available for photosynthetic production. This phenomenon is common in different plants like maize, wheat, barley, rice, potato (Wagg et al., 2021). This adaptation guarantees the allocation of resources to seed production, even in situations with limited water availability.

4.2 Drought Avoidance Response Mechanism

Drought avoidance (DA) is a plant adaptation strategy characterized by slow growth, aimed at maintaining water availability during stressful conditions by preserving high water potential in plant cells. This adaptation involves various morphological responses, such as root elongation, stomatal closure, leaf rolling, reduced leaf area and fewer leaves. These responses collectively enable plants to uphold high water potential, effectively conserving water. Plants employing DA mechanisms exhibit slower metabolism, minimal transpiration water loss, enhanced water absorption from roots, and improve overall WUE. Adaptations promoting DA may also involve maintaining higher ratios of root growth relative to shoot growth in anticipation of impending drought conditions (Khatun et al., 2021). These strategies collectively aid plants in preserving water availability and thriving in water-scarce drought environments.

4.2.1 Deep Root Response

Roots serve as the primary plant organs responsible for detecting changes in soil conditions, playing a crucial role in responding to water stress. During drought, plant leaves lose water faster than roots can absorb from the soil. To cope with limited water, plants adapt by minimizing transpiration and enhancing water absorption from the soil. Altering root structure significantly improves cereal crop yields, like rice, under DS. Studies show that modifications enhancing root diameter and depth correlate positively with overall plant Vigor in drought-stressed rice. Upland japonica rice, resistant to drought, develops extensive and deep root systems, while indica subspecies cope by shortening their growth period. Rain-fed rice varieties overcome soil hardpan layers with deep root systems, enhancing adaptability in DS (Kim et al., 2020). Most herbaceous plants feature fibrous root systems with delicate lateral roots for effective water absorption. In response to low soil moisture, plants allocate more resources to roots, adjusting carbon assimilation to promote rapid root growth towards moist soil layers. Root hairs increase surface area, drawing water from inaccessible pores. Severe drought prompts above-ground growth reduction, expanding the root system for increased water absorption. This leads to a higher root-to-shoot ratio in plants during severe drought (Ranjan et al., 2022).

4.2.2 Stomatal Closure Response

In response to DS, plants initially decrease transpiration by closing stomata, leading to reduced leaf water content, chlorophyll levels, chloroplast fragmentation, gas exchange, ion exchange between roots and shoots, and photosynthetic activity. This closure also hindered the uptake of CO_2, essential for photosynthesis, resulting in decreased transpiration and photosynthetic activity. Reduced transpiration limited the plant's ability to absorb nutrients through the roots and transport them to upper plant parts. However, maintaining leaf water potential was crucial as it enabled the plant to withstand low to moderate water stress, ensuring survival in challenging conditions (Oguz et al., 2022).

4.2.3 Leaf Rolling Response

Leaf rolling, seen in crops like *Triticum*, *Oryza* and *Zea* spp., boosts photosynthesis and grain yield and lessens transpiration and water loss during severe drought (Kadioglu et al., 2012). Transcription factors are vital regulators enhancing leaf rolling, aiding plant adaptability to water deficit conditions. Plants which exhibit delayed leaf rolling are generally less susceptible to drought, highlighting the importance of this adaptive mechanism. One study on rice proposed a mechanistic link between leaf rolling and DA. When drought conditions prevailed, there was a rapid decrease in stomatal conductance, effectively reducing water loss. Prior to the complete closure of stomata, the leaves of the rice plant rolled up as a protective response. As a result, the rate of water loss from rolled leaves was notably lower when compared to artificially flattened leaves (Wang et al., 2023).

4.3 Drought Tolerance Response Mechanism

Drought tolerance (DT) is a capacity of plants to survive despite being exposed to DS (water deficit). This is achieved through various physiological mechanisms including, enhancing potential of osmotic adjustment and increasing elasticity of cell wall to perpetuate tissue turgidity.

4.3.1 Osmotic Adjustment Response

Osmotic adjustment is vital for managing cell water and coping with DS in plants. The K^+ transporters play crucial role in this process, contributing to turgor-dependent cell growth and osmotic adjustment. These transporters are modulated by hormones like ABA and auxin. Furthermore, these modulate K^+ efflux in root cells, closure of stomata, and the formation of abscisic acid signalling complexes in plants facing DS (Osakabe et al., 2013). Pronounced osmotic adjustment aids to sustain high leaf water content, resulting in increased plant yield and biomass even under drought conditions. Additionally, this process results in osmolyte accumulation in the root region, promoting root expansion into deeper soil layers. This expansion allows the plant to access water from deeper soil sections, enhancing its ability to survive DS.

4.3.2 Solute Accumulation Response

Plants accumulate solutes like sucrose, proline, soluble sugars, amino acids, glycine and betaine during drought stress. These solutes serve as protective agents, intervening in cellular processes to maintain osmotic balance, membrane integrity and preserve enzymes and destroy active oxygen free radicals (Tiwari et al., 2016). Proline, notably, plays a critical role in sustaining cell osmotic potential, protecting against severe dehydration, and buffering cellular redox potential under water-deficient conditions (Boudjabi et al., 2015). Additionally, proline depicts as a signalling molecule, influencing processes such as mitochondria function, cell production, and cell death. Sugars serve a vital role as an alternative water source during water stress, creating a hydration shell surrounding the proteins. In wheat genotypes, particularly during the grain filling stage, an increased accumulation of soluble carbohydrates compared to the pre-anthesis stage contributes to proper grain production (Tyagi & Pandey, 2022).

4.3.3 High Abscisic Acid Synthesis Response

In drought conditions, plants synthesize abscisic acid in their roots, which is transported to the leaves which induces stomatal closure, limiting plant growth and enhancing stress adaptability. Drought-tolerant crops, such as barley, show a five-fold increase in abscisic acid compared to susceptible varieties, highlighting its crucial role in drought adaptation (Thameur et al., 2014). Abscisic acid also regulates aquaporin proteins, facilitating efficient water movement between plant cells, and influences other hormones like ethylene, linked to senescence.

5 Approaches to Alleviate/Mitigate the Adverse Effects of DS

Apart from plant reactions, there are other alternatives for limiting the drought effects, including genome editing, transgenic breeding process, omics techniques, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)/Cas system and biochemical approaches in conjunction with mechanical procedures like seed priming, foliar treatments, and traditional agro practices. Traditional and rapid breeding technologies may be used to assist in designing future crops that are drought-smart in order to satisfy the 'zero hunger' goal by enhancing osmotic adaptations, water extraction efficiency (WEE), water consumption efficiency (WCE), stomatal conductance (SC) (Raza et al., 2023).

5.1 Breeding Approach

5.1.1 Convectional Breeding

Conventional breeding, relying on empirical yield assessment, is challenged by drought's unpredictable nature in open situations (Galaitsi et al., 2016). Ability to understand plant's physiological route is crucial for gene sequence identification, quantitative trait loci (QTL) selection and QTL introgression (Medici et al., 2014). Screening resistant cultivars in open fields is impractical due to drought's inconsistent reactions; however, control is possible in protected environments (Ali et al., 2017). Experiments by Tollenaar and Lee (2002) exposed cultivars to both water scarcity and abundance across separate years. In 2010 De Vita et al. evaluated 65 durum wheat genotypes under various water regimes, noting that later-introduced cultivars typically outperformed due to greater adaptability and higher yield. Analysis done at the CIMMYT Norman E. Borlaug Research Station assessed 30 wheat cultivars from the past 50 years, revealing a group with good performance under sustained DS (Mondal et al., 2020). While conventional breeding remains significant for producing transgene-free crops with consistent yield attributes and superior nutritional value (Ahmar et al., 2020), the challenges of drought-response underscore the importance of controlled environments in cultivar screening.

In barren regions, an effective approach for breeding drought-resistant crops involves engineering the raffinose biosynthesis pathway. The galactose synthase gene (AtGolS), particularly AtGolS2, stimulates raffinose and galactinol accumulation in plants facing water deficiency, notably under DS. Expression of AtGolS2 in plants increases raffinose and galactinol levels, enhancing their proficiency to endure drought and protect against oxidative stress through ROS scavenging and appropriate solutes (Salvi et al., 2020). Metabolome analyses in rice and soybean revealed elevated raffinose and galactinol levels as responses to DS. Introducing AtGolS2 into crop plants enhances stress resilience in arid conditions, improving both drought tolerance and grain output (Selvaraj et al., 2017). AtGolS2 metabolic engineering emerges as a valuable strategy, proving instrumental in increasing crop yield during water scarcity situations (Honna et al., 2016).

5.1.2 Speed Breeding (SB)

Speed breeding, also known as rapid generation advance, is an approach of producing trivial plants from juvenile seeds in a controlled environmental condition while shortening the entire growth phase (Fikre et al., 2021). Another study by Kumar et al. (2023) also deciphered speed breeding of wheatgrass by varying photoperiod in a controlled environment. Future cultivars that are resistant to drought are capable of being produced through SB. Christopher et al. (2015) used SB methods to create a wheat cultivar that can withstand water scarcity; in just 18 months, the researchers developed up to F5 generation of stay-green inbred lines. Additionally, the study produced over 40,000 molecular markers that might be used to uncover new QTL linked to stay-green features.

5.2 Genomic Approach

Differentially expressed genes (DEGs) have been found using cutting-edge omics techniques, which may be used as biomarkers to create agricultural plants resistant to drought (Raza et al., 2021).

5.2.1 Genome-Wide Association Studies

Certain alleles crucial for genomics-assisted breeding (GAB) to develop drought-resistant agricultural plants can be identified through genome-wide association studies (GWAS) (Habib et al., 2020) reported 27 significant SNPs linked to increased seminal root length in maize, a key factor for DS tolerance. Stress marker genes ERD1 and RD20A were identified under DS (Huang et al., 2012). Research by Du et al. (2018) demonstrated that overexpression of GmFDL19, GmDREB2, GmWRKY27, GmMYB118 and GmMYB174 enhances plant drought tolerance. Drought resistance involves multiple genes and plant factors, resulting in integrated quantitative traits. Wheat RAC875/Kukri population is commonly used for DS tolerance studies, revealing a QTL on chromosome 3BL across 21 locations in Mexico and Australia. RAC875 increases yield by 12.5% under heat and DS, while Kukri boosts grain production by 9% in optimal conditions (Bonneau et al., 2013). Ahmed et al. (2021) employed 407 Diversity Arrays Technology markers to identify 104 significant QTL related to DS tolerance in 138 wheat seedlings. In soybean GWAS for DS, 15 QTL across 13 chromosomal regions explained 5.81% of phenotypic variance, with marker WPT-2356 correlating with the drought susceptibility index (Raza et al., 2023).

5.2.2 Transcriptomics

Novel insights in the analysis of genes and gene network's response towards DS provides the developments in RNA sequencing technology utilizing parallel transcriptome profiling. Furthermore, several gene functions under DS have been clarified by expressed sequence tags, RNA profiling employing microarrays, Affymetrix gene technologies and serial study of gene expression (Raza et al., 2023). Transcriptome analysis of both wild-type and mutant maize plants revealed a large number of DEGs (differentially expressed gene) and demonstrated that photosynthesis-associated gene communication was suppressed in the former but unaltered in the latter in the mutant crops under DS (Zhang et al., 2020). Singh et al. (2021) conducted research whereby they determined and verified the NAC gene expression patterns of three legume species—chickpea, pigeon pea, and peanut in DS circumstances. Ten genes from chickpeas, six from pigeon peas, and five from peanuts have been demonstrated to be DS-responsive potential genes due to expression analysis. These results imply that NAC transcription factors (TFs) are essential for many agricultural plants to acquire DS. Wang et al. (2021) used transcriptome analysis to identify genes that are linked with GmLHYs in soybean during DS. The dysfunctional mutant of GmLHYs substantially alters soybean drought-response pathways.

5.2.3 Transgenic Plants

In the last several decades, transgenic techniques have grown widely to improve the growth of plants in environments with restricted water supply (Raza et al., 2023). Harsh environmental factor including drought has major impact on quality and production of rice. OsESG1 an S-domain receptor (like kinase), has been found in rice and is known to have a role in the formation of early crown roots and the response to drought (Pan et al., 2020). Both local and foreign markets have a considerable demand for aromatic rice cultivars with distinctive odours. However, biotic and abiotic stressors have a major impact on their yields. In comparison to wild-type plants (Pusa Sugandhi 2), the transgenic aromatic rice variety showed improved resistance to drought and was linked with increased in relative amount of leaf water, decreased reticence of root and shoot lengths, decreased H_2O_2 accumulation, and elevated storage of proline and CAT. It also independently overexpresses the AtDREB1A and OsRab16A genes (Ganguly et al., 2020). Plants that have higher levels of cuticular wax have been shown to be more resilient to abiotic stressors. According to Wang et al. (2020), transgenic rapeseed plants that overexpressed the orthologs of 3-ketoacyl-CoA synthase, BnKCS1-1, BnKCS1-2, as well as the ortholog of ECERIFERUM, BnCER1-2 produced considerably more cuticular wax in comparison to wild-type plants and showed improved DS tolerance.

5.2.4 Metabolomics

Drought-related physiological processes were investigated using a UPLC-MS in a metabolic cross-profile between the genotypes of drought-tolerant (HX10) and drought-sensitive (YN211) wheat under DS (Guo et al., 2020). The DS proliferation indicators of genotype HX10 were greater than those of YN211; this may be attributed to its strong DT capacity, which also explains the high levels of different flavonoids, amino acids, organic acids, alkaloids as well as the high accumulation of metabolites such phenolics (Guo et al., 2020). Ma et al. (2021) analysed 5335 distinct metabolites of the 151,228 detected spectra with 3361 upregulated and 1794 downregulated, in order to examine the impact of DS on alfalfa metabolism employing nontargeted metabolite sequencing adopting gas chromatography–mass spectrometry. Skalska used flow infusion electrospray high-resolution mass spectroscopy

(HRMS) to undertake metabolomics analysis of juvenile leaves of 55 Turkish *Brachypodium distachyon* (L.) *Beauv.* accessions (Skalska et al., 2021) The findings showed that proline levels rose in all groups under DS additionally there were changes in polyphenolic metabolism, sugar and starch, antioxidant synthesis however, these alterations might have been typical physiological reactions to the drought, such as the provision of bioenergetic resources and adaptations to oxidative stressors.

5.2.5 CRISPR/Cas System

Numerous crop cultivars now exhibit higher levels of DS tolerance, thanks to conventional breeding and transgenic techniques. But under water constraint, the majority of these promising cultivars are unable to yield large quantities (Raza et al., 2023). Researchers prefer to modify cultivar genomes forbearance against array of abiotic stresses (including DS) using recently developed gene-modification tools like the cutting-edge Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) and CRISPR-associated-Cas proteins (CRISPR-Cas9) systems (Shinwari et al., 2020). Using the CRISPR-Cas9 technology, a gene that resists salt and drought was currently altered in the indica mega rice cultivar ‘MTU1010’. Wider leaves and reduced stomatal stimulation on the mutant cultivar improved leaf retained water under DS. It was determined that stomatal gene downregulation was the cause of the reduced opening of stomata in dst mutant rice plants (Santosh Kumar et al., 2020).

5.3 Biochemical and Mechanical Approaches

5.3.1 Phyto-Hormone Applications

Strigolactones, auxins, brassinosteroids (BR), gibberellic acid (GA), cytokines, jasmonic acid (JA), abscisic acid (ABA), ethylene serve as vital signalling phytohormones in regulating plant development during DS (Raza et al., 2022). GA aids in maintaining protein production, intracellular water balance in DS plants, reducing hypocotyl length and weight loss caused by water stress when applied to seedlings (Javid et al., 2011). Mousavi et al. (2022) suggested that foliar application to sugarcane of auxin at 3000 mg L^{-1} at mid-flowering enhances head number and grain production under DS. Kumari et al. (2018) suggested cytokines in wheat at 10 mg L^{-1} treatment promote increased photosynthetic matter, development, and resilience under DS Endogenous ABA synthesis, as reported by Vishwakarma et al. (2017), enriched plant turgor pressure, contributing to improved DS tolerance. Application of JA (0.5–10 μM) enhances antioxidant activities, increasing plant output and enhancing sugar beets DS resilience (Ghaffari et al., 2019). Adding salicylic acid to wheat indirectly boosts proline accumulation by elevating ABA levels. Phytohormones such as BR and ethylene play crucial roles in addressing various environmental challenges, including DS (Raza et al., 2023).

5.3.2 Biochar Application

An efficient agronomic tactic to tone down the damaging effects of climate alteration and DS is biochar (BC) application, sometimes known as the 'black gold' of agriculture (Sohi et al., 2010). The application of biochar at 30 t ha^{-1} mitigated the adverse consequences of DS in rapeseed, resulting in diminished content of EL, H_2O_2, and MDA. This was achieved by increasing the activities of enzymes such as SOD by 63%, POD by 48% and CAT by 62%. These findings suggest that applying biochar could be an ecological way to improve growth of rapeseed cultivar during drought conditions (Khan et al., 2021). Applying 37.18 g/kg of biochar can be a useful technique to boost wheat grain production by reducing the negative impacts of DS. In comparison to the control treatment, the application of biochar greatly reduced the impact of the drought by increasing the number of spike length (6.52%), thousand grain weight (6.42%), fertile tillers (19.50%), number of grains per spike (3.07%), economic output (13.92%) biological (9.43%) (Haider et al., 2020).

5.3.3 Plant–Microbe Relationship

The application of commensal microorganisms like arbuscular mycorrhizal fungi (AMF) and PGPR may enhance plants' ability to retain water. AMF inoculation is method employed to increase plant resilience to drought (Chen et al., 2020). They enhance the soil's integrity and plant adaptability to water crisis circumstances. With a blend of cellular, nutritional, physical, and physiological impacts, AMF increases drought resistance. It is true that they can increase seedling endurance, plant absorption and conveyance of water, change in the morphology of roots, enhance the activity of hormones derived from plants, and hasten the extraction of ROS from plant cells (Zhang et al., 2019; Rydlová & Püschel, 2020). Phyllosphere bacterial culture inoculation was used to reduce the effects of biotic and abiotic stressors on rice cultivars (Devarajan et al., 2022). Additionally, development biomass and the drought tolerance index were all boosted. In a similar vein, it has been claimed that *Trichoderma* sp., and especially *Trichoderma harizianum*, is useful for DS and can be used to help rice survive dry spells (Silletti et al., 2021).

5.3.4 Osmoprotectants

Key osmoprotectants in plants under water stress, like glycine betaine, mannitol, proline, trehalose, and fruton, are commonly applied externally during different growth stages or as seed treatments. This safeguards subcellular structures, enhances antioxidant enzyme function, and aids osmotic adjustment in stressed plants (Elkelish et al., 2020). Topical proline application boosts internal proline levels, improving DR in crops (Semida et al., 2021). Spermidine (polyamine) meritoriously enhances water stress resistance in crops like barley and wheat, acting as antioxidants, maintaining equilibrium, stabilizing membranes, and signalling with other molecules (Sallam et al., 2019). Higher polyamine concentrations in plants correlate with improved osmotic adjustment, reduced water loss, enhanced photosynthesis, and detoxification under drought conditions. Additionally, glycine betaine, a crucial osmolyte, increases drought tolerance in rice, barley, and maize cultivars, protecting thylakoid membranes, sustaining photosynthetic efficiency, and facilitating osmotic modification (Ashraf & Foolad, 2007).

5.3.5 Agricultural Practices

Seed Sowing and Plant Density(PD)

The timing of the planting/sowing is crucial for reducing the catastrophic consequences of DS during the reproductive phase. Early sowing of maize increased its development greatly because it avoided the probable drought and high heat in the middle of summer (Lu et al., 2017). According to Mandić et al. (2020), early sowing of soybeans in Serbia had similar results; however, late sowing exposed the crops to reduced moisture and possible DS. Studies support that soil's outermost layer is supported by higher plant density. Plants are able to utilize this water in subsequent phases of development. For instance, in dry conditions, high PD of maize crop reduced leaf area index, which in turn reduced evapotranspiration and increased WUE (water utilization efficiency) (Guo et al., 2021). Nadeem et al. (2019) found that certain high-density legume plants produced lower yields and more lodging under DS.

Seed Priming

The significant short-term strategy to lessen negative effects of drought onto cultivar is identified as seed priming. This pre-sowing strategy aims to get ready seed for radicle outgrowth without causing radicle protrusion in the procedure by starting the germination process in the seed's metabolic mechanism (Nawaz et al., 2013). In comparison to non-primed seeds, primed seeds exhibit better rate of germination and evenness due to their more efficient germination mechanism (Moosavi et al., 2009). Seed priming is used in cultivars such as wheat, maize, and chickpeas to remove the negative impact of DS (Seleiman et al., 2021). Recently, the severity and frequency of droughts have increased due to the implementation of the directly seeded rice (DSR) technology in aerobic rice cultivation (Farooq et al., 2011). Different osmotica were utilized for DSR in water-scarce environments, and outcomes showed that $CaHPO_4$ and KCL osmopriming increased agricultural yield and productivity (Nawaz et al., 2016). According to reports, primed seeds under drought-induced circumstances increased WUE in wheat crops by 44% in comparison of non-primed seeds. In 2020, Khan et al. primed two varieties of rapeseed, Huayouza 9 (HZ 9) and Shenguang 127 (SG 127), with melatonin (MT) and GA3. Comparing GA3 and MT-primed plants to no-primed plants, the former showed less decline in seed quality characteristics and less loss in physical characteristics, yield, and yield components. Their findings showed that, in both normal and drought-stressed environments, the superior efficiency of primed-issued plants was linked to increased proline accumulation and better elimination of ROS via stimulating antioxidant enzymes. However, in comparison to the no-prime treatment, GA and MT priming also enhanced the morphological features, seed yield and qualitative characteristics in open arena settings.

Application of Selenium and Potassium

Selenium (Se) application benefits plants facing water deficits by producing suitable solutes and reducing oxidative damage. Se administration enhances plant development, mitigates oxidative stress, counters light-induced oxidative damage, synthesizes antioxidants during senescence, and regulates plant water balance to withstand DS (Özen et al., 2019). During DS, applying potassium (K) helps alleviate negative effects and sustain plant output by supporting internal regulatory systems (Hasanuzzaman et al., 2018). Increased K content in plants may lead to oxidative damage and reactive oxygen species formation during photosynthesis (Seleiman et al., 2020). Plants under stress require a higher K dose to maintain carbon dioxide fixation in photosynthesis (Zahoor et al., 2017). Insufficient K treatment during DS results in poorer photosynthesis rates, emphasizing the necessity of a certain K amount for optimal physiological functions (Brestic et al., 2018). Applying K, either topically or as a soil additive, is crucial for optimal physiological functioning and improved crop yield in water-scarce regions (Kumar et al., 2019). Jatav et al. (2012) noted increased chlorophylls, carotenoids, and yield metrics in wheat cultivars treated with 10 mM K_2O, with relative water content (RWC) rising with higher potassium dosages under all irrigation regimes.

Hydrogels Approach

The advancement and growth of plants are positively impacted by improved physical, chemical and biological description of the soil brought by hydrogel soil supplement. By adding it to the soil, it prolongs the period during when crops survive DS, which was previously shortened by the soil's hydraulic conductivity and water loss (Jerszurki et al., 2017). The hydrogel coating boosted the plants' life period by producing enough soil moisture. Thus, its incorporation into the soil is advantageous for rhizosphere water conservation, especially in dry and semi-arid conditions and drought-affected areas (Ayangbenro and Babalola., 2021). When soil was treated with polymers, less water evaporated during evaporation process than when soil was left without a hydrogel supplement (Saha et al., 2020).

5.4 Nano-particle and Nano-fertilizer Approach

Nanoparticles (NPs) enhance plants' drought resilience through diverse mechanisms, including regulating stomatal conductance, improving photosynthesis, osmolyte concentration, WUE, nutrient acquisition, express of drought-response genes and antioxidant activity (Kandhol et al., 2022). Si-NPs and zinc oxide NPs improve wheat cultivars' drought resilience while zinc and ferrous nanoparticles together enhance plant drought resilience (Seydmohammadi et al., 2020). Titanium dioxide (TiO_2) NPs alleviate DS impacts by activating chemicals and mitigating negative consequences (Seleiman et al., 2020). Cu and Ag NPs reduce DS effects on lentils (Seleiman et al., 2020) and nano-silica improves certain plants' drought resistance. Zinc oxide NPs increase SOD and POD levels in wheat as a drought-proofing mechanism, with zinc and copper NPs also enhancing wheat resilience

(Maswada et al., 2020). NPs reduce water loss through stomatal closure, mitigate oxidative stress by lowering ROS and enhance the antioxidant defence system (Kandhol et al., 2022). Genetically modified NPs act as targeted delivery vehicles for CRISPR/Cas mRNA and siRNA, altering gene expression under stress conditions (Ran et al., 2017). Nano fertilizers over the past decade have boosted productivity, decreased costs and stabilized production by reducing abiotic and biotic stressors (Kashyap et al., 2017). Sedghi et al. (2013) suggested nano-Zn fertilizer elevates lipids, proteins, amino acids, and chlorophyll *b* levels, significantly contributing to drought tolerance. Rizwan et al. (2019) reported improved wheat grain growth, chlorophyll content, gas exchange properties, and Zn concentration with Zn nano fertilizers, concurrently reducing oxidative stress.

6 Conclusion

DS exerts a pervasive impact on plants throughout their life cycle, spanning from germination to maturity, disrupting various physiological, metabolic, and biochemical processes and impeding overall plant productivity. In response to DS, plants have evolved mechanisms to enhance drought tolerance. Plants have adopted various strategies to mitigate its effect through alterations in growth patterns, structural dynamics, and reductions in transpiration loss through stomatal conductance. Additionally, adaptations such as modification in dynamic root-to-shoot ratio, leaf rolling, rise in root length, compatible solutes accumulation, increase in transpiration efficiency, osmotic and hormonal regulation, and delayed senescence help plants in coping with water deficit stress. Furthermore, breeding strategies, molecular and genomic perspectives, as well as omics technologies have considerably enhanced the DS tolerance in plants. Certain agricultural practices like seed priming, application of growth hormones, osmoprotectants, Si, Se, and K are also effective under water-scarce conditions. Moreover, the use of microbes, hydrogels, nanoparticles and metabolic engineering techniques regulates antioxidant enzyme activity, facilitating plant adaptation to DS by maintaining cellular homeostasis and alleviating the adverse effects of water stress. Hence, these innovative strategies not only provide a deeper understanding of plant responses to DS but also hold the potential significance in increasing plant productivity in dry environments and enhancing global food security in the face of changing climatic conditions.

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Part II

Disaster Management and Preparedness

The Interplay of Fossil Fuels and Natural Disasters

Rachan Karmakar, Vijay Tripathi, Pradeep Kumar, Narpinder Singh, and Rajesh Kumar

1 Introduction

The link between fossil fuels and natural disasters is pivotal in today's environmental discourse (Farghali et al., 2023). Fossil fuels—coal, oil, and natural gas—have fueled industrial growth but also spurred environmental shifts, notably through greenhouse gas emissions, intensifying climate change (Rahman & Wahid, 2021). This destabilizes the climate, escalating natural disaster frequency and intensity globally (Shivanna, 2022). Understanding this link is crucial (Abbass et al., 2022), given the threats posed by disasters like hurricanes and wildfires (Chaudhary & Piracha, 2021). It sheds light on disaster mechanisms, socioeconomic injustices, and the urgency of transitioning to sustainable energy sources (Lawler et al., 2013; Kinol et al., 2023; Ma et al., 2023a, b). This knowledge informs resilient, equitable solutions for the future (Lawler et al., 2013; Kinol et al., 2023; Ma et al., 2023a, b).

R. Karmakar (✉) · P. Kumar
Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India
e-mail: rachan.in.air@gmail.com

V. Tripathi
Department of Microbiology, Graphic Era (Deemed to be University), Dehradun, India

N. Singh
Department of Food Science and Technology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

R. Kumar
Department of Chemistry, SSJ University Campus-Almora, Almora, India

N. Singh, S. A. Babu (eds.), *Climate Crisis and Sustainable Solutions*,
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Table 1 Environmental consequences and risks of fossil fuel usage

Environmental consequences	Risks
Air pollution	Accidents (e.g., oil spills, and pipeline leaks)
Water pollution	Devastation of ecosystems and communities
Deforestation	Greenhouse gas emissions
Greenhouse gas emissions	Climate change
Exacerbation of natural disasters (e.g., hurricanes, wildfires, and droughts)	

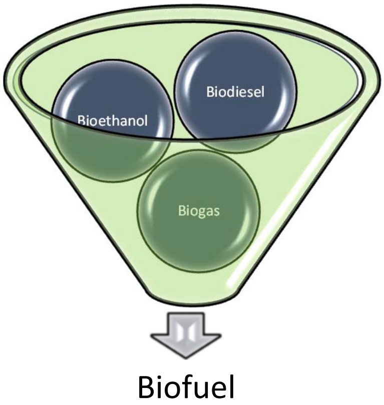

Fig. 1 Types of biofuels

2 Fossil Fuels: Overview and Impact

Fossil fuels, which include coal, oil, and natural gas, have long served as the primary sources of energy worldwide, driving industrialization and economic growth. However, their extensive use has led to significant environmental consequences, including air and water pollution, deforestation, and greenhouse gas emissions (Perera, 2017). These emissions contribute to climate change, exacerbating natural disasters such as hurricanes, wildfires, and droughts (Donaghy et al., 2023) (Table 1). Moreover, the extraction and transportation of fossil fuels pose risks of accidents, such as oil spills and pipeline leaks, which can devastate ecosystems and communities (Emerson et al., 2021; Roychowdhury et al., 2011; Karmakar et al., 2012). Thus, while fossil fuels have fueled human progress, their reliance comes at a profound cost to both the environment and human well-being, highlighting the urgent need for transitioning to renewable energy sources (Osman et al., 2022).

2.1 Definition and Types of Fossil Fuels

Fossil fuels encompass a group of hydrocarbon-based energy sources formed from the remains of ancient organisms over millions of years. These resources include coal, oil (petroleum), and natural gas, each with distinct properties and extraction methods. Coal, the most abundant fossil fuel, forms from the decay of plant matter in swampy environments, while oil originates from the decomposition of marine organisms in sedimentary rock layers (Wallace & Hobbs, 2006). Natural gas, composed primarily of methane, results from similar processes but typically forms in association with oil deposits or through microbial action in deep underground reservoirs (Mundra & Lockley, 2024) (Fig. 1). Despite their differences, all fossil fuels share the characteristic of releasing carbon dioxide when burned, contributing to climate change and environmental degradation (Baz et al., 2022). As society grapples with the impacts of fossil fuel consumption, understanding their definition and varieties is essential for exploring alternatives and mitigating their adverse effects (Martins et al., 2019).

2.2 Extraction, Production, and Consumption Patterns

Extraction, production, and consumption patterns of fossil fuels are intricate components of global energy dynamics, deeply influencing economies, societies, and the environment (Peša & Ross, 2021). Extraction involves the retrieval of fossil fuels from geological deposits through various methods such as drilling, mining, and fracking. Production processes refine these raw materials into usable forms like gasoline, diesel, and natural gas. Consumption patterns dictate how these fuels are utilized across sectors like transportation, industry, and residential energy use. These patterns vary widely across regions and evolve over time due to factors such as technological advancements, economic fluctuations, and shifting energy policies. However, despite differences, the overarching trend has been one of increasing demand, particularly in rapidly industrializing nations, driving extensive environmental impacts including greenhouse gas emissions, habitat destruction, and air and water pollution (Keong, 2021a, b). As societies strive for sustainability, understanding and reshaping these patterns are paramount for transitioning toward cleaner and more efficient energy systems (Hassan et al., 2024).

2.3 Environmental Impacts of Fossil Fuel Usage

The environmental impacts of fossil fuel usage are profound and multifaceted, encompassing a range of detrimental effects on ecosystems, air and water quality, and global climate patterns. The combustion of fossil fuels releases greenhouse gases such as carbon dioxide, methane, and nitrous oxide, which contribute significantly to global warming and climate change (Cloy & Smith, 2023). This warming exacerbates extreme weather events, disrupts ecosystems, and threatens biodiversity. Moreover, fossil fuel extraction processes, including mining, drilling, and fracking, can lead to habitat destruction, water contamination, and soil degradation, disrupting fragile ecosystems and endangering wildlife (Scanes, 2018). Additionally, the release of pollutants like sulfur dioxide, nitrogen oxides, and particulate matter from burning fossil fuels contributes to air pollution, respiratory illnesses, and smog formation, further compromising human health and well-being (Sharma et al., 2023; Kumar et al., 2017; Karmakar et al., 2019). Addressing these environmental impacts requires a concerted effort to transition toward renewable energy sources and adopt sustainable practices to mitigate the adverse effects of fossil fuel usage (Chen et al., 2023; Karmakar et al., 2020).

3 Factors Contributing to Natural Disasters and Case Studies

Natural disasters result from a complex interplay of various factors, including geological, meteorological, hydrological, and human-induced elements. Geological factors such as tectonic plate movements, volcanic eruptions, and seismic activity contribute to events like earthquakes, tsunamis, and volcanic eruptions (Mazzorana et al., 2019). Meteorological factors encompass weather phenomena such as hurricanes, tornadoes, floods, and droughts, influenced by atmospheric conditions and climate patterns (Jaffrés et al., 2018). Hydrological factors involve the interaction of water bodies, including riverine and coastal processes, which can lead to flooding, storm surges, and landslides. Human activities such as deforestation, urbanization, and unsustainable land use practices can exacerbate the severity and frequency of natural disasters, amplifying their impacts on communities and ecosystems (Parven et al., 2022). Case studies such as Hurricane Katrina in 2005, the Tohoku earthquake and tsunami in Japan in 2011, and the Kerala floods in India in 2018 illustrate the devastating consequences of natural disasters and highlight the importance of effective disaster preparedness, mitigation, and response strategies to minimize their toll on lives and livelihoods (Okazumi & Nakasu, 2015).

4 Intersection of Fossil Fuels and Natural Disasters

The link between fossil fuels and natural disasters is intricate, with significant implications for society and the environment. Fossil fuel processes drive greenhouse gas emissions, worsening climate change, and intensifying disasters like hurricanes and wildfires (Zhao et al., 2022). Infrastructure like pipelines and refineries can suffer from extreme weather, causing accidents like oil spills and worsening environmental damage (Soeder & Borglum, 2019). This reliance creates a feedback loop, amplifying climate change and disaster risks (Leal-Arcas et al., 2023). Transitioning to renewables and sustainable practices is vital to break this cycle and reduce global impacts (Karmakar et al., 2017b).

4.1 Impact of Fossil Fuel Usage on Climate Change

The impact of fossil fuel usage on climate change is profound and undeniable. Burning fossil fuels releases carbon dioxide and other greenhouse gases into the atmosphere, trapping heat and leading to global warming (Bolan et al., 2024). This warming disrupts climate patterns, resulting in more frequent and severe extreme weather events such as hurricanes, heatwaves, floods, and droughts. Additionally, the melting of polar ice caps and glaciers, driven by rising temperatures, contributes to sea-level rise, threatening coastal communities and ecosystems (Heikkilä et al., 2022). Moreover, fossil fuel extraction processes, including mining, drilling, and fracking, disrupt habitats, pollute air and water, and release methane, a potent greenhouse gas. The consequences of continued fossil fuel usage are dire, with the potential for irreversible damage to the planet's climate system and ecosystems (Kumar, 2022). Addressing climate change requires a rapid transition away from fossil fuels toward renewable energy sources and sustainable practices to mitigate its impacts and secure a livable future for generations to come (Ragit et al., 2013; Karmakar et al., 2021).

4.2 Amplification of Natural Disasters by Fossil Fuel Activities

Fossil fuel activities worsen natural disasters, amplifying their severity and frequency globally. Extraction, production, and consumption emit greenhouse gases, heating the atmosphere and intensifying disasters (Saraf & Bera, 2023; Hosseini, 2022). This leads to more extreme weather events like hurricanes and wildfires (Hou et al., 2022; Zhao et al., 2022). Infrastructure vulnerability during disasters results in oil spills and environmental damage (Dong et al., 2022; Pine, 2006). Fossil fuel activities also destabilize ecosystems, increasing landslide and sinkhole risks (Haldar, 2020; Vinayagam et al., 2024).

4.3 Vulnerability of Fossil Fuel Infrastructure to Natural Disasters

The vulnerability of fossil fuel infrastructure to natural disasters presents a significant challenge, as these facilities are often situated in regions prone to extreme weather events and geological hazards. Oil refineries, drilling rigs, pipelines, and storage facilities are susceptible to damage and disruption during hurricanes, floods, earthquakes, and wildfires, leading to environmental contamination, economic losses, and threats to public safety (Dong et al., 2022). For instance, coastal refineries and offshore drilling platforms are at risk of storm surges, high winds, and flooding during hurricanes, as demonstrated by the damage caused by Hurricane Katrina to oil infrastructure in the Gulf of Mexico in 2005. Similarly, pipelines transporting oil and gas can rupture or leak due to ground movement during earthquakes or landslides, as seen in incidents such as the 2010 San Bruno pipeline explosion in

California (Ramírez-Camacho et al., 2017). Moreover, the increased frequency and severity of wildfires in regions with extensive oil and gas infrastructure, such as California and Alberta, Canada, pose threats of ignition, structural damage, and air pollution, further highlighting the vulnerability of fossil fuel facilities to natural disasters (Pine, 2006). Addressing this vulnerability requires proactive measures such as improving infrastructure resilience, implementing stricter safety regulations, and diversifying energy sources to reduce reliance on fossil fuels in high-risk areas (Kyriakopoulos & Sebos, 2023). Additionally, incorporating climate risk assessments and disaster preparedness plans into energy infrastructure planning and decision-making processes can help mitigate the impacts of natural disasters on fossil fuel facilities and enhance overall resilience in the face of a changing climate.

5 Environmental and Socioeconomic Consequences

The environmental and socioeconomic consequences of fossil fuel usage are far-reaching and profound, spanning from local ecosystems to global climate systems and from individual communities to entire nations (Perera, 2017). Environmentally, the combustion of fossil fuels releases greenhouse gases such as carbon dioxide and methane, contributing significantly to climate change and resulting in rising global temperatures, shifting weather patterns, and increased frequency and intensity of extreme weather events (Karmakar et al., 2017a). This has devastating impacts on ecosystems, leading to habitat loss, biodiversity decline, and ecosystem degradation. Moreover, fossil fuel extraction processes, including mining, drilling, and fracking, cause habitat destruction, air and water pollution, and soil contamination, posing threats to wildlife, ecosystems, and human health (Schroth, 2018). Communities living near fossil fuel extraction sites often bear the brunt of environmental pollution, health hazards, and socioeconomic disparities, experiencing higher rates of respiratory illnesses, water contamination, and economic instability (Perera, 2017). Transitioning away from fossil fuels toward renewable energy sources is essential to mitigate these environmental and socioeconomic consequences, fostering a more sustainable, equitable, and resilient future for both people and the planet (Chen et al., 2022).

5.1 Environmental Degradation and Pollution

Fossil fuel usage leads to severe environmental degradation and pollution, harming ecosystems and human health globally. Extraction, production, and combustion release pollutants into the air, water, and soil (Chu & Karr, 2017). Air pollution from combustion emits sulfur dioxide, nitrogen oxides, and particulate matter, causing respiratory diseases and acid rain (Perera, 2017). Water pollution results from toxic chemical discharge, harming aquatic life and human health (Landrigan et al., 2020). Soil degradation occurs through land disturbances and spills, affecting ecosystems and agriculture (Bhattacharyya et al., 2015). Urgent transition to cleaner energy sources is crucial to mitigate further damage (Perera, 2017).

5.2 Economic Costs and Losses

The economic costs and losses incurred by disasters related to fossil fuel extraction, production, and usage are staggering, encompassing direct damages, indirect impacts, and long-term consequences for economies and communities worldwide (Totten, 2018). Natural disasters such as oil spills, pipeline leaks, and industrial accidents result in immediate costs related to cleanup, remediation, and infrastructure repair, often running into billions of dollars. Moreover, these disasters disrupt economic activities in affected regions, causing job losses, business closures, and disruptions to supply chains, leading to reduced productivity and economic growth (Welch et al., 2023). The long-term economic impacts of fossil fuel-related disasters extend beyond the initial event, with lingering effects on industries such as tourism, agriculture, and fisheries, as well as on public health expenditures and insurance premiums. Additionally, the reliance on fossil fuels perpetuates a cycle of economic vulnerability, as fossil fuel-dependent economies are susceptible to price volatility, market fluctuations, and geopolitical tensions, hindering diversification and sustainable development efforts (Guan et al., 2023; Mensah, 2019). Transitioning toward renewable energy sources and adopting resilient, low-carbon economies is crucial for mitigating the economic costs and losses associated with fossil fuel-related disasters, promoting economic stability, and building a more sustainable future for communities and economies globally.

5.3 Social Disruption and Humanitarian Challenges

Social disruption and humanitarian challenges stemming from disasters related to fossil fuel activities pose significant threats to communities, exacerbating vulnerabilities and inequalities while undermining social cohesion and well-being (Totten, 2018). Disasters such as oil spills, industrial accidents, and environmental pollution have immediate and long-lasting impacts on human health, livelihoods, and quality of life, particularly for marginalized and vulnerable populations. These events can lead to displacement, loss of homes, and disruption of essential services, causing physical and psychological trauma and exacerbating social inequalities (Andrews et al., 2021). Humanitarian challenges emerge as communities struggle to access clean water, food, healthcare, and other basic necessities in the aftermath of disasters, while also contending with the loss of livelihoods and economic opportunities (Bazaanah & Mothapo, 2023). Furthermore, the burden of response and recovery efforts falls disproportionately on already overstretched local governments, civil society organizations, and communities, exacerbating resource constraints and social tensions (Levine et al., 2023). Addressing social disruption and humanitarian challenges requires comprehensive and inclusive disaster preparedness, response, and recovery strategies that prioritize the needs and rights of affected communities, promote social resilience and equity, and foster community-led approaches to building sustainable and resilient futures in the face of fossil fuel-related disasters (Ma et al., 2023a, b).

6 Mitigation and Adaptation Strategies

Mitigation and adaptation strategies are essential for addressing the challenges posed by fossil fuel-related disasters. Mitigation efforts focus on reducing greenhouse gas emissions, transitioning to renewable energy sources, and implementing sustainable practices to prevent or minimize the impacts of future disasters (Fawzy et al., 2020). Adaptation strategies involve building resilience in communities and ecosystems, enhancing early warning systems, and implementing disaster preparedness and response plans to cope with the impacts of ongoing climate change and environmental degradation. By combining mitigation and adaptation measures, societies can work toward building a more sustainable and resilient future in the face of fossil fuel-related disasters (Lawler et al., 2013).

6.1 Transitioning to Renewable Energy Sources

Transitioning to renewable energy sources is crucial for mitigating the environmental, social, and economic impacts of fossil fuel usage. Renewable energy sources such as solar, wind, hydroelectric, and geothermal power offer sustainable alternatives that produce minimal greenhouse gas emissions and reduce dependence on finite fossil fuel reserves (Strielkowski et al., 2021). By harnessing the abundant and clean energy provided by renewable sources, societies can mitigate climate change, improve air and water quality, and protect ecosystems and biodiversity. Moreover, transitioning to renewable energy creates opportunities for job creation, economic growth, and technological innovation, fostering a more equitable and resilient energy system (Kumar et al., 2017). However, a successful transition requires supportive policies, investment in infrastructure, and public engagement to overcome barriers and accelerate the adoption of renewable energy technologies on a global scale (Qadir et al., 2021). By embracing renewable energy, societies can build a more sustainable and prosperous future for generations to come.

6.2 Enhancing Resilience and Preparedness

Enhancing resilience and preparedness is vital for communities to withstand and respond effectively to the impacts of fossil fuel-related disasters. This involves strengthening infrastructure, implementing early warning systems, and developing robust emergency response plans tailored to the specific risks posed by fossil fuel activities. Building community resilience also entails fostering social cohesion, empowering local stakeholders, and promoting equitable access to resources and information (Jewett et al., 2021). Moreover, investing in disaster preparedness measures, such as training programs, public education campaigns, and community drills, can help mitigate the human and economic costs of disasters while reducing vulnerability and enhancing adaptive capacity. By prioritizing resilience and preparedness, societies can better cope with the uncertainties of a changing climate and build more sustainable and inclusive futures in the face of fossil fuel-related challenges (Santos et al., 2022).

7 Lessons Learned, Successful Initiatives, and Best Practices

Lessons learned from past fossil fuel-related disasters have underscored the importance of proactive measures, community engagement, and sustainable practices in mitigating risks and enhancing resilience (Carmen et al., 2022). Successful initiatives and best practices have emerged across various sectors, offering valuable insights and models for addressing the complex challenges posed by fossil fuel activities (Chipangamate & Nwaila, 2024). For instance, the adoption of renewable energy technologies and energy efficiency measures has proven effective in reducing greenhouse gas emissions, diversifying energy sources, and promoting economic development while minimizing environmental impacts (Karmakar et al., 2017b). Additionally, community-based approaches to disaster preparedness, such as participatory risk assessment, early warning systems, and decentralized response mechanisms, empower local stakeholders and enhance adaptive capacity, fostering resilience in vulnerable communities (Ma et al., 2023a, b). Furthermore, regulatory frameworks and industry standards that prioritize safety, environmental protection, and corporate responsibility play a crucial role in preventing accidents, minimizing environmental pollution, and ensuring accountability in fossil fuel operations (Ragit et al., 2013). By learning from past experiences, leveraging successful initiatives, and adopting best practices, societies can navigate the challenges of fossil fuel-related disasters more effectively while advancing toward a cleaner, safer, and more equitable energy transition (Vakulchuk et al., 2020).

8 Future Outlook and Recommendations

The future outlook for addressing the challenges posed by fossil fuel-related disasters hinges on concerted efforts to transition toward renewable energy sources, enhance resilience, and promote sustainable development (Roychowdhury et al., 2011). Policymakers, stakeholders, and communities must prioritize ambitious climate action, incorporating mitigation and adaptation measures into policy frameworks and investment decisions. This includes phasing out fossil fuel subsidies, investing in renewable energy infrastructure, and supporting research and innovation in clean technologies (Karmakar et al., 2012). Moreover, fostering international cooperation, building partnerships, and sharing knowledge and resources are essential for addressing the transboundary impacts of fossil fuel activities and promoting global resilience. By embracing sustainable practices, empowering communities, and working collaboratively, societies can navigate the uncertainties of a changing climate and build a more resilient, equitable, and sustainable future for all (Kioupi & Voulvoulis, 2019).

8.1 Anticipated Trends and Challenges

Anticipated trends in addressing fossil fuel-related disasters include an increased focus on renewable energy adoption, climate resilience building, and sustainable development practices (Jaiswal et al., 2022). However, significant challenges remain, including political inertia, vested interests in the fossil fuel industry, and inadequate funding for mitigation and adaptation efforts. Additionally, the impacts of climate change are expected to intensify, leading to more frequent and severe natural disasters, which will strain resources and infrastructure. Addressing these challenges will require political will, cooperation between governments and stakeholders, and innovative solutions that prioritize environmental sustainability and social equity (de Almeida et al., 2024). Moreover, the transition away from fossil fuels must be just and inclusive, ensuring that vulnerable communities are not left behind and that the benefits of renewable energy adoption are shared equitably. By confronting these challenges head-on and embracing sustainable solutions, societies can build resilience and chart a path toward a more sustainable and prosperous future (Totten, 2018).

8.2 Policy Recommendations and Actions

Policy recommendations and actions to address fossil fuel-related disasters should prioritize a comprehensive approach that integrates mitigation, adaptation, and resilience-building measures. This includes implementing stringent regulations and standards to reduce greenhouse gas emissions, transitioning to renewable energy sources, and phasing out subsidies for fossil fuel extraction and consumption (Karmakar et al., 2017a). Additionally, policies should promote sustainable land use practices, ecosystem restoration, and disaster risk reduction measures to enhance community resilience and protect vulnerable populations. Investing in green infrastructure, clean technologies, and climate-resilient development can help build adaptive capacity and reduce the impacts of future disasters (Argyroudis et al., 2022). Furthermore, fostering international cooperation, sharing best practices, and mobilizing resources for climate action are essential for addressing the global nature of fossil fuel-related challenges. By enacting bold policy initiatives and taking decisive actions, governments and stakeholders can mitigate the risks posed by fossil fuel activities and pave the way for a more sustainable and resilient future (Keong, 2021a, b).

8.3 Research Directions for Further Understanding

Research directions for further understanding of fossil fuel-related disasters should focus on interdisciplinary approaches that examine the complex interactions between human activities, environmental factors, and climate change (Lauf et al., 2014). This includes studying the impacts of fossil fuel extraction, production, and consumption on ecosystems, biodiversity, and human health, as well as identifying vulnerable populations and assessing their adaptive capacity. Additionally, research efforts should explore innovative technologies and strategies for mitigating environmental pollution, reducing greenhouse gas emissions, and promoting sustainable energy transitions (Wang et al., 2021). Furthermore, advancing scientific knowledge on the drivers and dynamics of natural disasters, such as hurricanes, floods, and wildfires, and their relationship to fossil fuel activities can inform more effective risk assessment, preparedness, and response measures. By fostering collaboration between researchers, policymakers, and communities, research can contribute to evidence-based decision-making and contribute to building resilience in the face of fossil fuel-related challenges (Carmen et al., 2022).

9 Conclusion

Therefore, understanding the intricate relationship between fossil fuel consumption and natural disasters is imperative for addressing the urgent challenges of our time. Fossil fuel usage not only drives industrialization and economic growth but also exacerbates environmental degradation and intensifies the frequency and severity of natural disasters. The reliance on fossil fuels amplifies the impacts of climate change, leading to disruptions in weather patterns and exacerbating extreme events like hurricanes, wildfires, and floods. Furthermore, the infrastructure associated with fossil fuel industries is vulnerable to the impacts of natural disasters, resulting in environmental contamination, economic losses, and threats to public safety. Transitioning to renewable energy sources, enhancing resilience and preparedness in communities, establishing robust policy frameworks, and fostering international cooperation are crucial steps in mitigating the risks posed by fossil fuel-related disasters and building a more sustainable and resilient future. Despite significant challenges, concerted efforts and collaborative actions can pave the way for a safer, healthier, and more equitable world for generations to come.

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Fire Hotspot and Aerosol Climatology Observation over South Asia Using Satellite Data

Ashish Kumar Dubey, Yogesh Kant, Nilanjana Sengupta, A. S. Madhusudanacharyulu, and D. Mitra

1 Introduction

Aerosols are microscopic particles suspended in the air with substantial effects on the climate, air quality and human health. Natural phenomena like dust storms and volcanic eruptions and human activity like industrial emissions, vehicle exhaust and biomass burning can be the source of these pollutants. The South Asian region, which includes nations like India, Pakistan, Bangladesh and Sri Lanka, is characterized by a complex interaction of climatic patterns, population density and various emission sources, making it particularly susceptible to aerosol pollution. This region has several different anthropogenic and natural sources of aerosol pollution. Forest fire and biomass burning are examples of natural sources and anthropogenic sources, that majorly contribute to aerosol loading. The identification of fire hotspots in the South Asian region as well as the characterization of aerosol climatology have been the focus of numerous studies. For instance, in the Indo-Gangetic Plain, a region known for intense agricultural activities and biomass burning and a significant hotspot of aerosol emissions in South Asia (Gautam et al., 2009), looked at the seasonal variability of aerosol pollution. They discovered that a major factor in the region's elevated AOD levels during the post-monsoon season was biomass burning.

Pinpointing and studying the spatiotemporal variability of fire hotspots is essential to comprehending how biomass burning contributes to aerosol pollution. The study by Banerjee et al. (2021) focused on the climatology of aerosols at a time when haze normally predominates in South and Southeast Asia (Vadrevu et al., 2019) analysed fire trends in South and Southeast Asia (S/SEA) using information from VIIRS and MODIS for the years 2012–2016 (Shaik et al., 2023) studied the

A. K. Dubey (✉) · Y. Kant · N. Sengupta · D. Mitra
Indian Institute of Remote Sensing, ISRO, Dehradun, India

A. S. Madhusudanacharyulu
Department of Physics, Raghu Engineering College, Visakhapatnam, India

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spatiotemporal variability of biomass burning in the different states of India and identified seven regional hotspots of biomass burning using MODIS (2003–2018) active fire points data.

The study (Blake Cohen et al., 2017) investigated the links between changes in land use, fires, precipitation, and aerosols over Southeast Asia by conducting a thorough analysis of 13 years' worth of remotely sensed data from numerous satellites and the AERONET network. The research showed that although Southeast Asia is a significant source of smoke emissions, smoke that is carried from other regions also influences Southeast Asia. Southeast Asia's northern regions see two yearly AOD peaks: one during the local fire season and a smaller peak brought on by a mix of regional smoke sources and the movement of aerosols from fires in the region's south, possibly including human-caused sources in South Asia. A study by Kant et al. (2022) observed a 21% increase in stubble fires over Punjab and Haryana regions over the last two decades, which increased 17% aerosol loading in the NCR region.

In this research, the active fire points data from satellite-based sensors, SNPP-VIIRS, is used to calculate fire density maps and AOD data is used to study the climatology of aerosol loading over the study period for 10 years (2013–2022) observations. The objective is to characterize the aerosol climatology and locate fire hotspots in the South Asian region by evaluating the active fire point data records. The present research objectives are to study the trend of fire occurrences over the South Asia region during 2013–2022. To analyse the climatology of aerosol loading over the region during 2013–2022 and identify pollutant emitting hotspots from these fire prone areas.

2 Study Area

The study is conducted over South Asia and Myanmar region which comprises nine countries namely India, Pakistan, Nepal, Bhutan, Bangladesh, Afghanistan, Sri Lanka, Maldives and Myanmar. Due to its geographical characteristics, seasonal fluctuations and the effect of multiple weather systems, South Asia presents a varied spectrum of climatic conditions. The region is known for high levels of aerosol pollution, primarily due to dust storms, forest and stubble fire, biomass burning activities, various anthropogenic activities, brick kilns, industrial emissions, fog, smog clubbed with natural meteorology anthropogenic activities and natural sources (Dey & Di Girolamo, 2011; Kumar et al., 2018; Srivastava et al., 2012). Industrial emissions, vehicular exhaust, open waste burning, and agricultural practices contribute to the release of particulate matter (PM), including fine $PM_{2.5}$ and coarse PM_{10}. Dust storms and the burning of solid fuels for cooking contribute to significant aerosol pollution in the region. This not only affects air quality but also leads to haze events and reduced visibility, which impacts health.

3 Material and Methodology

3.1 SNPP VIIRS Active Fire Points

To generate a fire density map daily active fire points from SNPP-VIIRS satellite at 375 m spatial resolution was downloaded from 2013 to 2022. SNPP VIIRS has been providing data for the active fire points since 2013 at a spatial resolution of 375 m. The 375 m I-band data has good agreement in hotspot detection and the spatial resolution of the 375 m data provides a greater response over fires of relatively small areas and provides improved mapping of large fire perimeters. The confidence of the data is the value that helps users gauge the quality of individual hotspot/fire pixels. Confidence values are set to low, nominal and high. Low confidence pixels are associated with areas of Sun glint and lower relative temperature anomaly (<15 K) in the mid-infrared channel I4. Nominal confidence pixels are free of potential Sun glint contamination during the day and marked by strong (>15 K) temperature anomalies. High-confidence fire pixels are associated with saturated pixels (Schroeder et al., 2014). For the current study, the Nominal confidence dataset was used as it showed a strong >15 K temperature anomaly. These nominal confidence fire points were filtered from the dataset for all the months from 2013 to 2022. Climatological monthly fire density files were made from the available 10 years' data. From the Fire Maps, the hotspot zones were identified. In those hotspot regions, comprehensive study was done to find the number of fires in each season in each hotspot zone.

3.2 SNPP VIIRS Aerosol Optical Depth

The VIIRS daily level-2 Deep Blue aerosol data at 6-min data granules is downloaded during 2013–2022. This orbit-level product has an at-nadir resolution of 6 km × 6 km and progressively increases away from the nadir. Viewed differently, this product's resolution accommodates 8 × 8 native VIIRS moderate-resolution (M-band) pixels that nominally have ~750 m horizontal pixel size. The L2 Deep Blue AOD data products, at 550 nm wavelengths, are derived from particular VIIRS bands using two primary AOD retrieval algorithms: Deep Blue algorithm over land, and the Satellite Ocean Aerosol Retrieval (SOAR) algorithm over ocean (Levy et al., 2015; Sawyer et al., 2020).

The data for AOD 500 nm was acquired from the Suomi NPP-VIIRS at a 6-min resolution on daily basis. The climatological average of AOD for each month was calculated from the daily data of 10 years duration (2013–2022). The fire hotspots were identified using the fire maps, and the average value for the AOD in that hotspot for all the seasons was calculated. The maps and graphs were made for each season.

4 Results and Discussion

4.1 Aerosol Climatology

The daily data of the AOD of SNPP VIIRS at 550 nm over the study area was processed and the Monthly Climatology of the AOD was mapped for the extent of the South Asian region. The values of AOD varied from the Range of 0–1.3. Some outlier values of up to three have been identified, which may be the cloud-contaminated values. Figure 1 shows the long-term (2013–2022) 4-monthly mean of the AOD over the study region. The AOD variation over the study extent for different months is January (0.58), February (0.38), March (0.71), April (0.42), May (0.67), June (0.42), July (0.53), August (0.24), September (0.23), October (0.24),

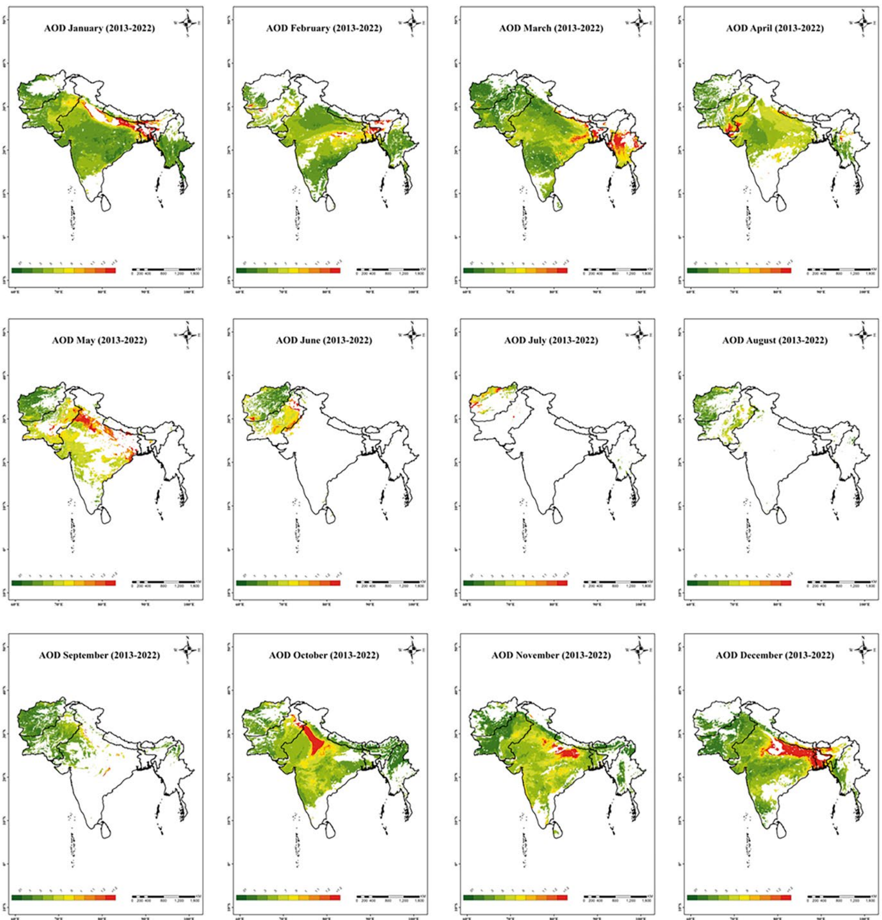

Fig. 1 Climatology of the monthly mean of aerosol optical thickness over the South Asian region

November (0.91) December (0.55). The observed annual AOD average for India is (0.43), Pakistan (0.40), Afghanistan (0.19), Bangladesh (0.19), Sri Lanka (0.18), Nepal (0.31), Bhutan (0.07) and Myanmar (0.25). The statistics for 10 years show AOD variation as +3.20%, +0.33%, 0.22%, 4.36%, −0.22%, 6.02%, −4.15%, −1.86% per year over India, Pakistan, Afghanistan, Bangladesh, Sri Lanka, Nepal, Bhutan and Myanmar respectively (Fig. 2).

The climatological and seasonal variation of aerosol loading over South Asian countries was also studied. Satellite observation and data show high aerosol loading during winter (DJF) and Spring (MAM) (Fig. 3) owing to biomass burning (mainly forest and stubble fires) and other anthropogenic activities, low temperature and boundary layer conditions during winters, while forest and stubble fires and dust storms in Spring mainly in the countries concentrated over India, Nepal, Pakistan, Myanmar. The meteorology and wind trajectories bring dust and smoke along with local anthropogenic loading over Bangladesh, which results in high aerosol loading during winters and spring.

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4.2 Fire Distribution Analysis

The daily active fire data of over South Asia was downloaded and plotted. From the plot in the South Asian Region, India has the highest number of annual fires, with average (578,177) fires (Fig. 4 and Table 1). This fire is all the fires combined, i.e., natural as well as anthropogenic induced fires (forest fires and biomass burning). India is followed by Myanmar with average (344,362), Pakistan (57,806), Nepal (30,779), Bangladesh (10,176) and Sri Lanka (7334) (Fig. 5). The statistics show fire variation as +5.00%, +0.79%, +3.86%, +37.80%, −0.01% and +1.66% per year over India, Myanmar, Pakistan, Nepal, Bangladesh and Sri Lanka.

4.3 Fire Hotspot

From the climatological long-term observation (Fig. 6) over the region and from our analysis it is established that there exists a continuous aerosol pollution source (hotspot) due to fire activity over the sub-regions of western Indo-Gangetic Plain (IGP), central IGP, Part of NE India and Western Myanmar and central eastern region of India (Fig. 7). This results in emitting aerosol particulates in the atmosphere predominant during Winter, Autumn and Spring seasons.

In some regions, we have observed a continuous larger number of fires in the last 10 years (2013–2022) during Winter, Spring and Autumn. These hotspots were persistent over a few pockets/sub-regions in the study area which is susceptible to natural or anthropogenic biomass-burning fires. Hence, we identify these regions as The Western Indo-Gangetic Plain, Central Indo-Gangetic Plain Part of Northeast India and Western Myanmar and Central and Eastern region of India.

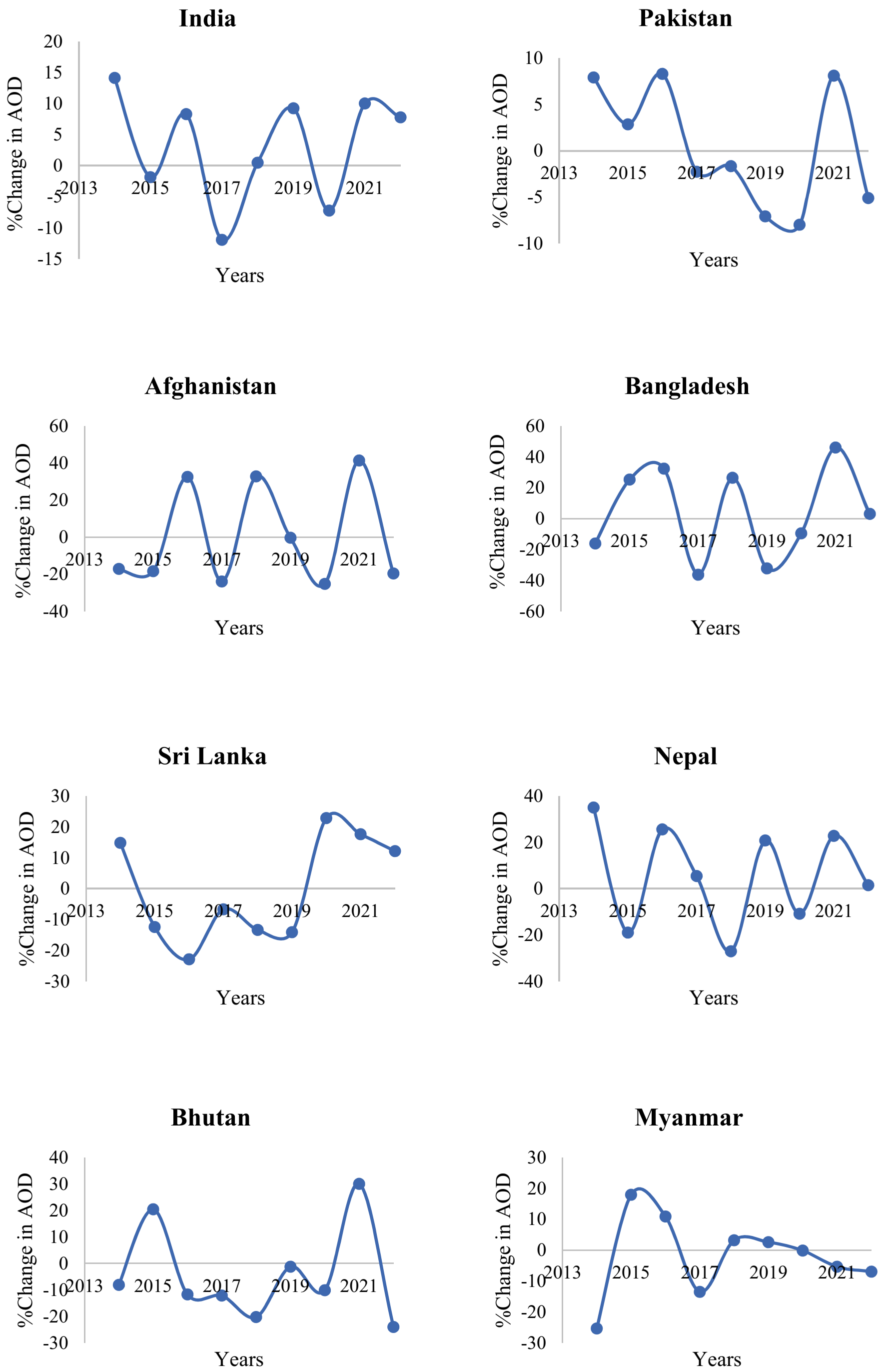

Fig. 2 Yearly % change in AOD values over different countries in South Asia

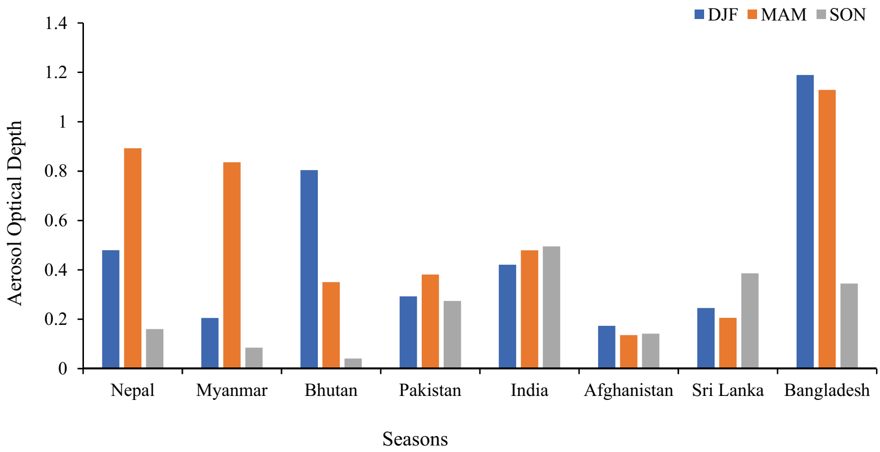

Fig. 3 Seasonal AOD variation in different countries

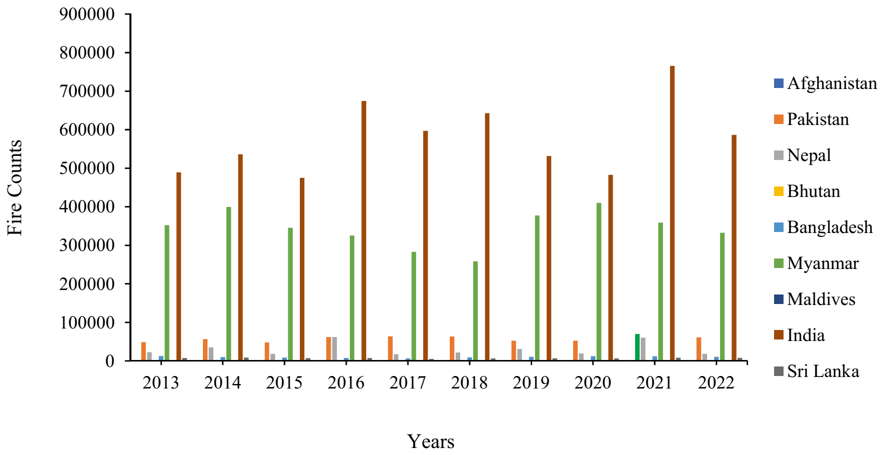

Fig. 4 Annual fire occurrences in different countries

In these hotspot zones, Seasonal Fire maps have been made, and the number of fire counts per year has been plotted. We have studied the number of fire occurrences seasonally over the identified hotspots for 10 years (2013–2022). Figure 8 shows the seasonal fire variability over the study region.

4.3.1 Western Indo-Gangetic Plain

During the winter season, this Western Indo-Gangetic Plain region experiences an average of 3995 fires per season. During this season, it is observed that the number of fires is increasing over the years. In the spring season this region experienced average 15,170 fires per season. The number of fire occurrences in this season is high over this region. In Autumn season this region experiences approximately an

Table 1 Yearly fire counts

	India	Pakistan	Nepal	Bangladesh	Myanmar	Afghanistan	Sri Lanka	Bhutan	Maldives
2013	489,144	48,846	22,666	12,800	352,424	1254	7546	850	4
2014	536,159	56,488	35,245	10,245	399,533	945	8526	604	4
2015	475,239	48,199	18,654	8549	345,771	765	7465	507	15
2016	674,484	61,946	62,026	7536	325,409	1196	7548	902	38
2017	596,996	63,923	17,722	6631	282,971	1442	5492	850	29
2018	642,985	63,608	21,997	9376	258,615	865	6574	588	20
2019	531,719	52,648	31,300	10,967	377,444	857	7186	606	27
2020	482,826	52,287	19,354	12,475	410,159	2196	6854	854	29
2021	765,761	68,987	60,359	12,153	358,754	1551	8246	867	21
2022	586,458	61,131	18,473	11,025	332,549	487	7902	624	12

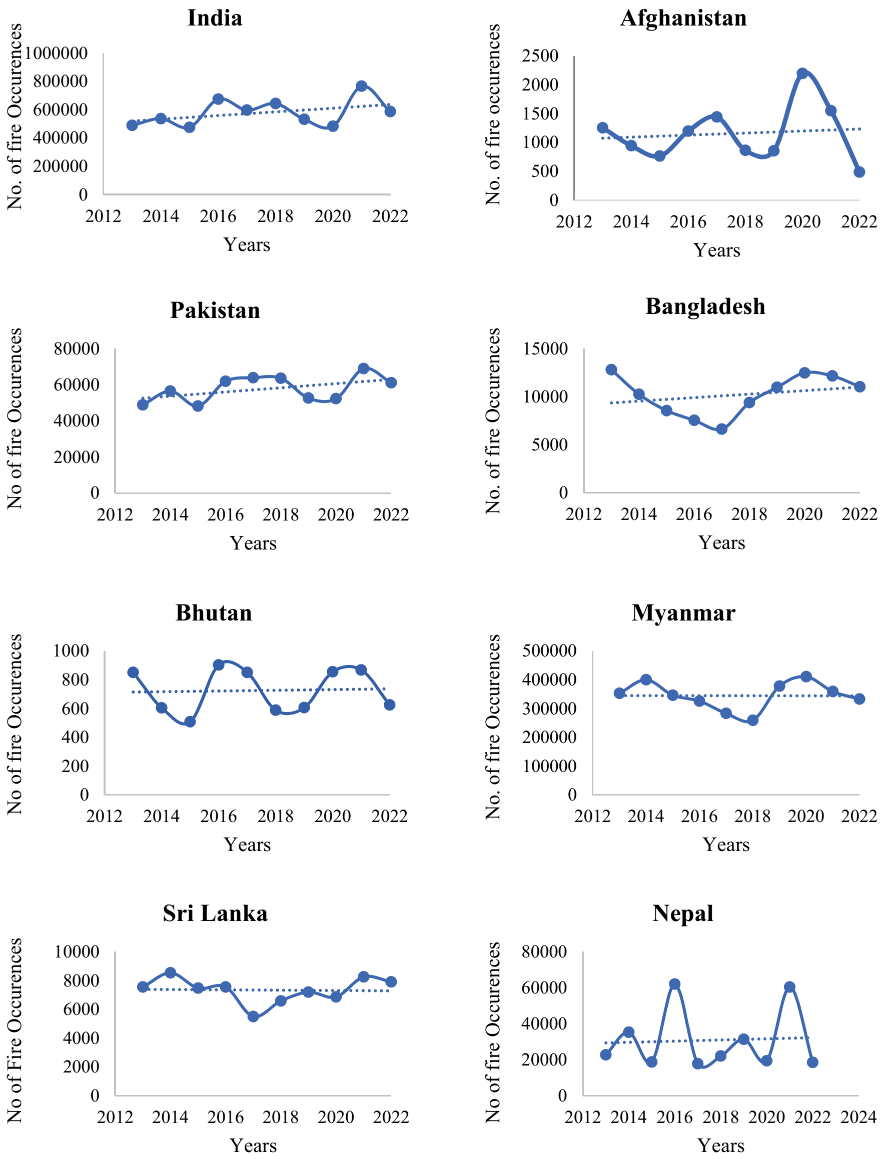

Fig. 5 Annual trend in fire occurrences over various South Asian countries as observed from SNPP-VIIRS at 375 m resolution

average of 60,702 fire per season per year. One of the main causes for these fires is the crop residue burning over the eastern Pakistan, Punjab and Haryana region of India (Fig. 9).

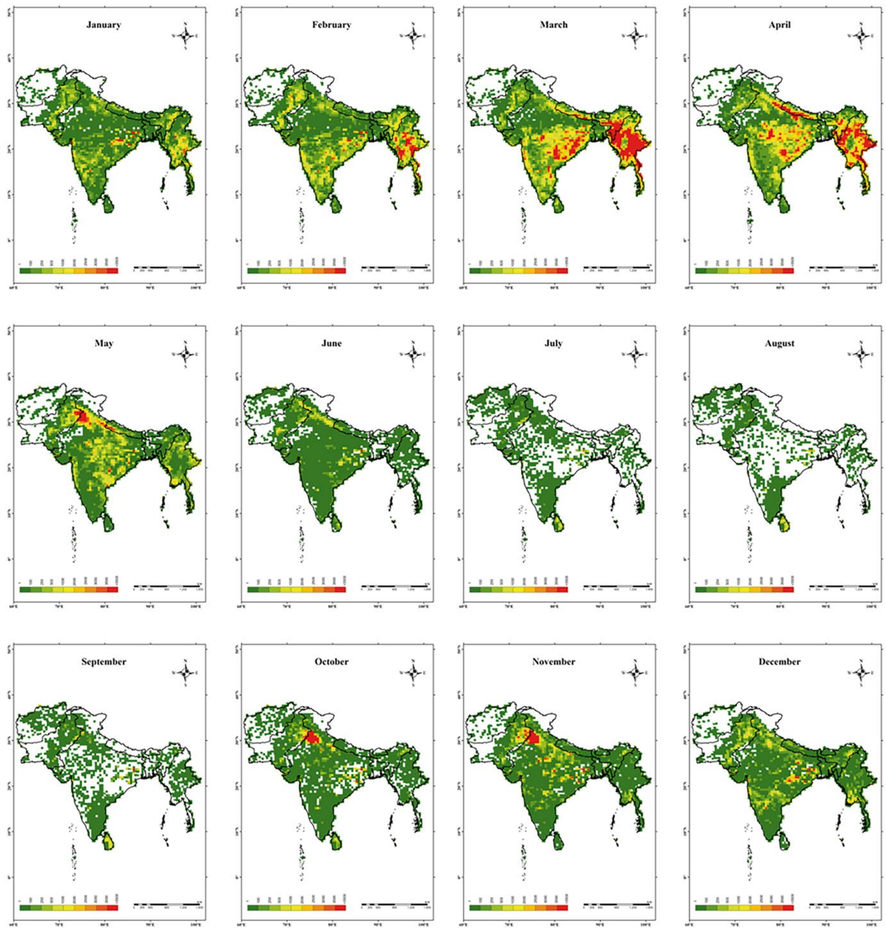

Fig. 6 Climatological (2013–2022) monthly active fire counts as observed from SNPP-VIIRS over the South Asian region at 0.5° resolution

4.3.2 Central Indo-Gangetic Plain

The Central Indo-Gangetic Plain is another fire hotspot region where the fire has been persistent throughout the years. The average fire in the Winter (5893), Summer (2411), Autumn (5306) and Spring (26,473). During the spring season the region experiences the Indian summer season, where the temperature is very high, and due to this, natural forest fires and cropland fire is common phenomena (Fig. 10).

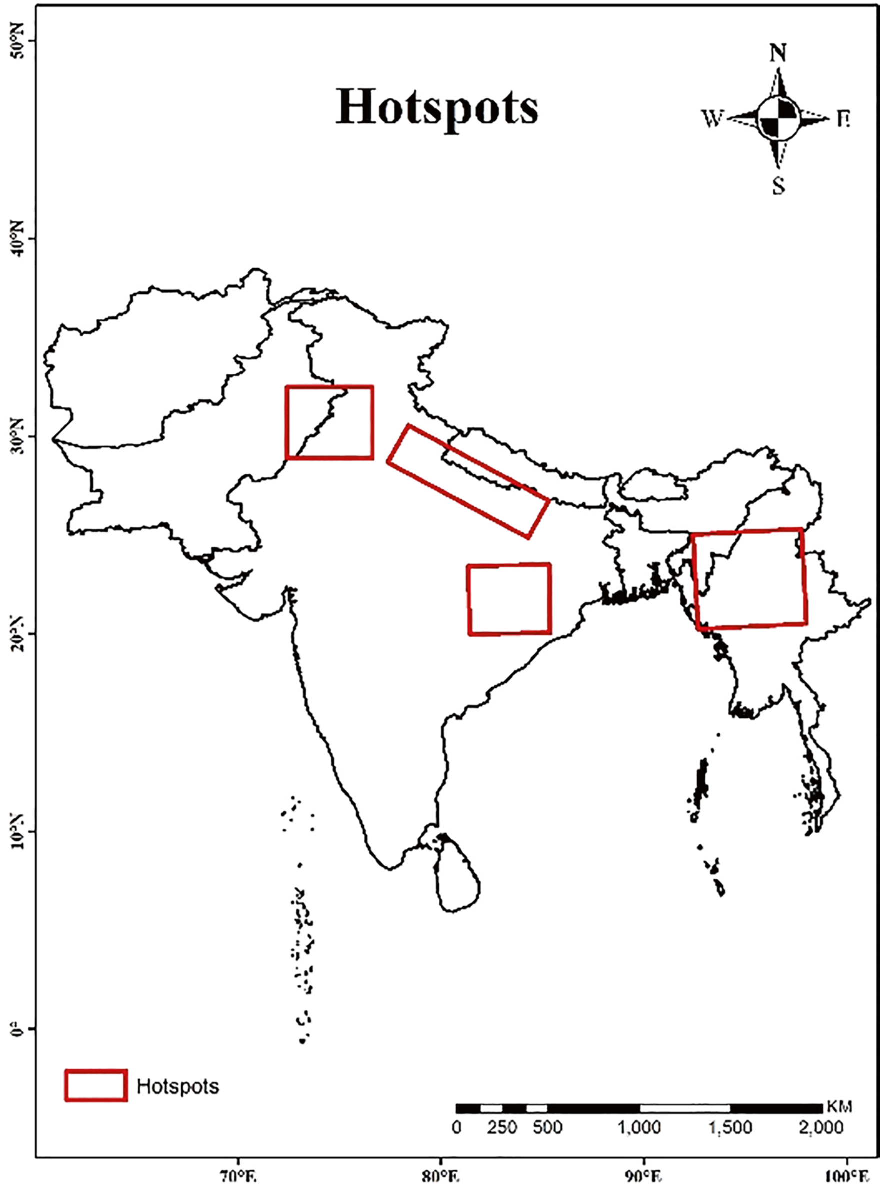

Fig. 7 Hotspot map over the study area

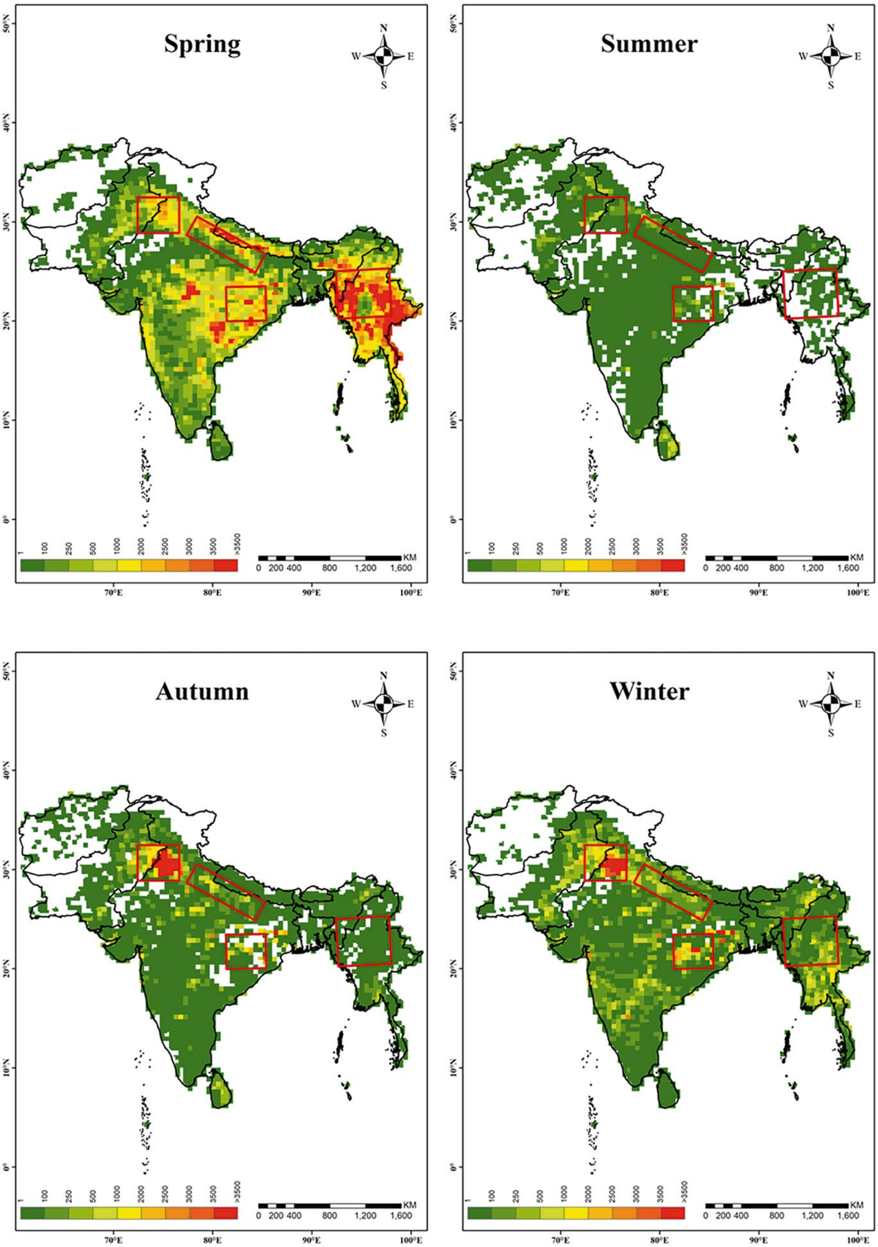

Fig. 8 Fire map with hotspot region in different seasons

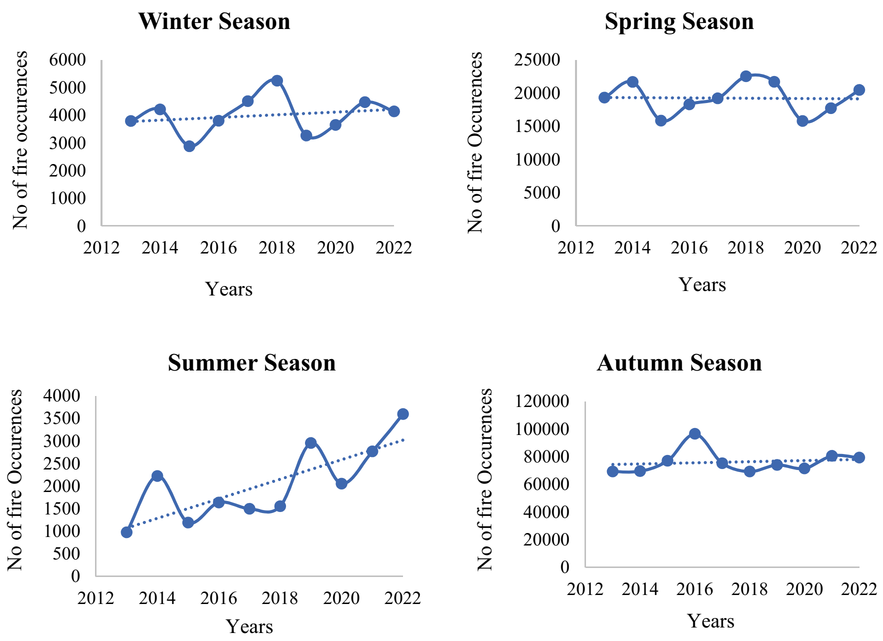

Fig. 9 Fire trends in Western Indo Gangetic Plain in different seasons

4.3.3 Part of Northeast and Western Myanmar Region

The part of Northeast of India and Western Myanmar is another hotspot region where the fire is persistent throughout the year. It is observed from the data that the average number of fire for Winter (21,426), Spring (107,480), Summer (1946), Autumn (5208). This high numbers of fires during the spring season is due to the natural forest fires since this region is densely covered with forest so the forest fire is common phenomenon (Fig. 11).

4.3.4 Central and Eastern Region of India

The Central and Eastern part of India is the identified hotspot for the fire since this region is mostly covered with forest thus forest fire is natural in this region. Here it can be observed from the statistics that the average number of fires in Winter (15,489), Spring (26,428), Summer (1946) and Autumn (2508) (Fig. 12).

4.4 Seasonal AOD Variability over Hotspots

The seasonal average value of the AOD is calculated over the Fire Hotspots that have been identified from the climatological fire maps for the years 2013–2022. We can see the variation in the AOD values in different seasons (Fig. 13). This concentration may be related to the fire that has been happening in that region or other

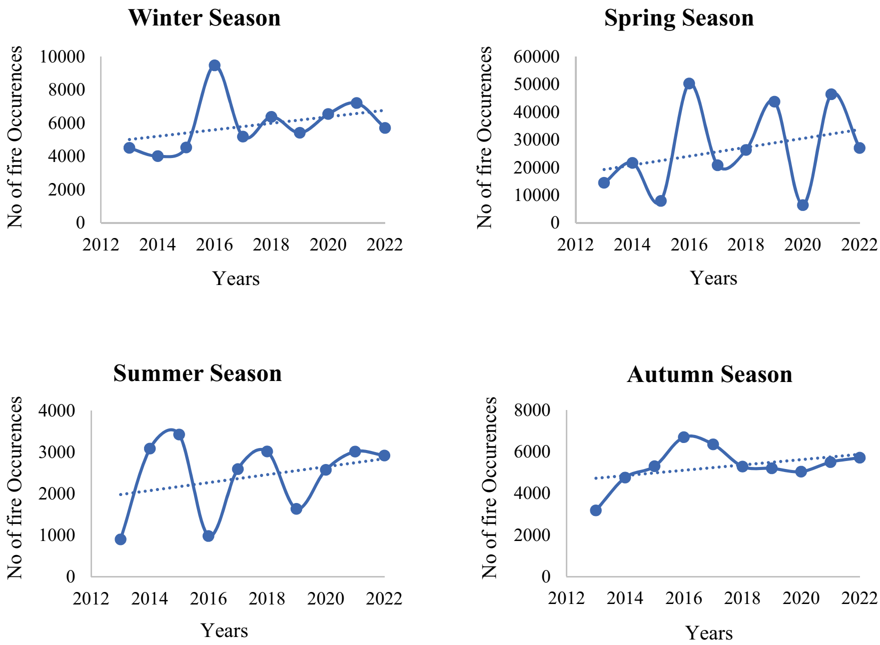

Fig. 10 Fire trends in Central Indo Gangetic Plain in different seasons

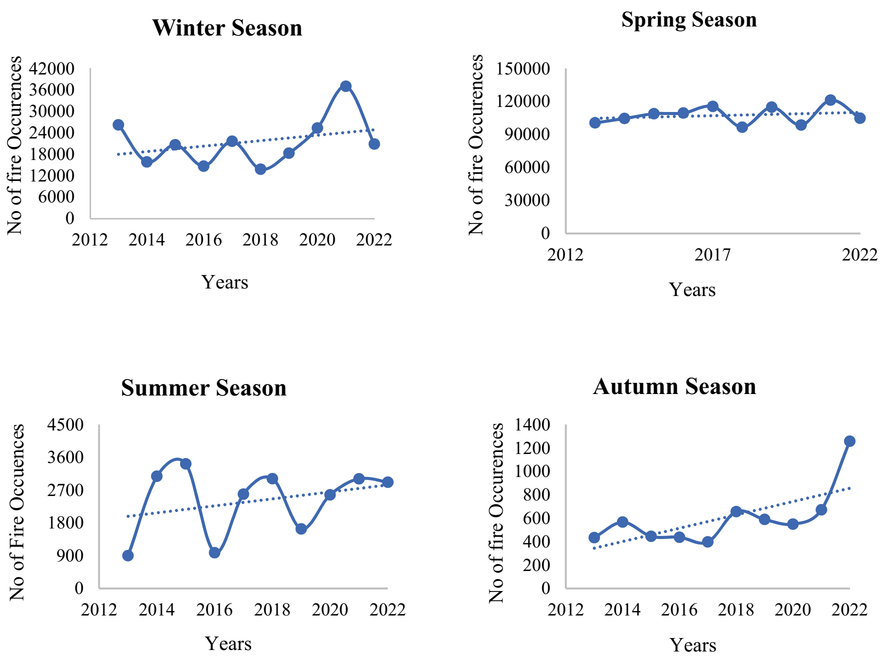

Fig. 11 Fire trends in part of North East and western Myanmar region in different seasons

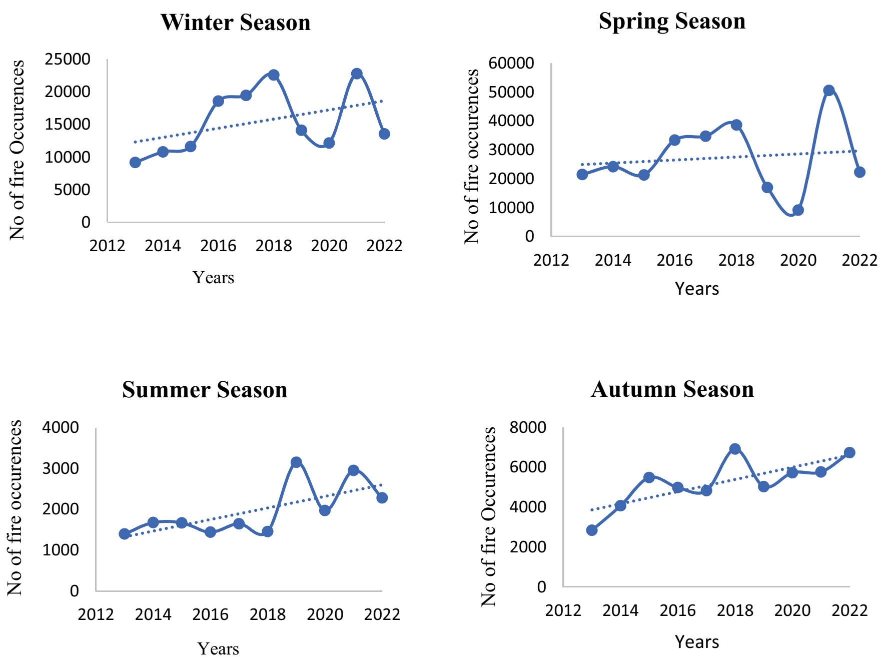

Fig. 12 Fire trends in the Central and Eastern Region of India

anthropogenic activities that have been happening over that region. Figure 13 shows the seasonal maps of AOD along with the hotspots marked over it.

The value of the AOD in this Western Indo-Gangetic Plain during the spring (0.72) and autumn seasons (0.67) (Fig. 14a). During this season, there is heavy biomass burning in this region. Seasonal variability of AOD in Central Indo-Gangetic Plain shows the AOD in the winter (0.67), spring (0.6) and autumn seasons (0.64) (Fig. 14b). In the hotspot region of Northeast and western Myanmar, the value of the AOD during the spring season (0.87) and autumn (0.63) (Fig. 14c) in this area. This area is mostly covered the forest thus, the forest fire contributes to the AOD concentration over this region, among other anthropogenic factors. In this region of Central and Eastern region of India during the spring season, the average values of AOD are (0.61). The summer season is the monsoon season in this area thus, the concentration is low (0.10) (Fig. 14d).

5 Conclusion

The study provides insight into the climatological fire and, thereby associated aerosol pollution trend analysis for different countries in the South Asia region (including Myanmar) in the last decade. An upward trend in fire occurrences has been noted across several South Asian countries during the period 2013–2022, i.e., +5.0%

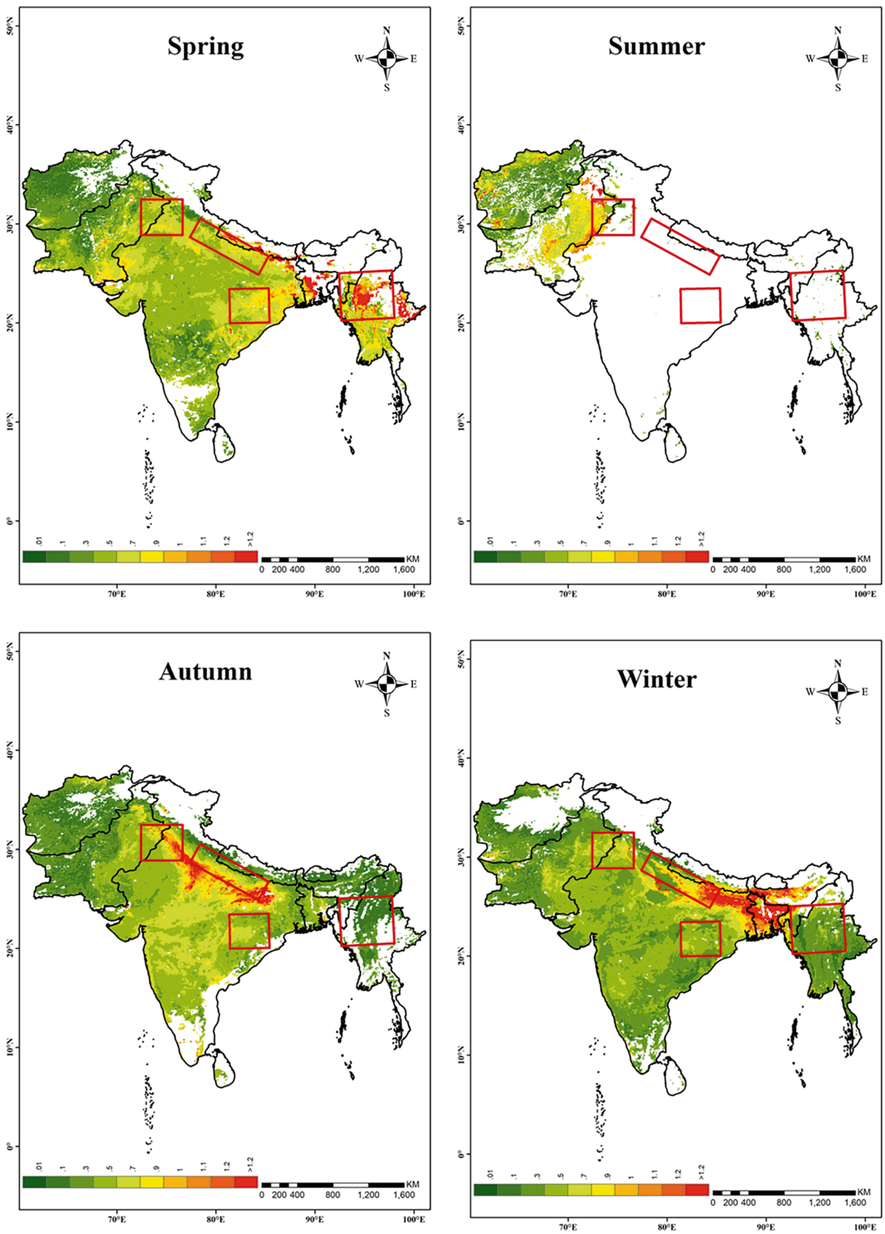

Fig. 13 Seasonal AOD variability over hotspot region

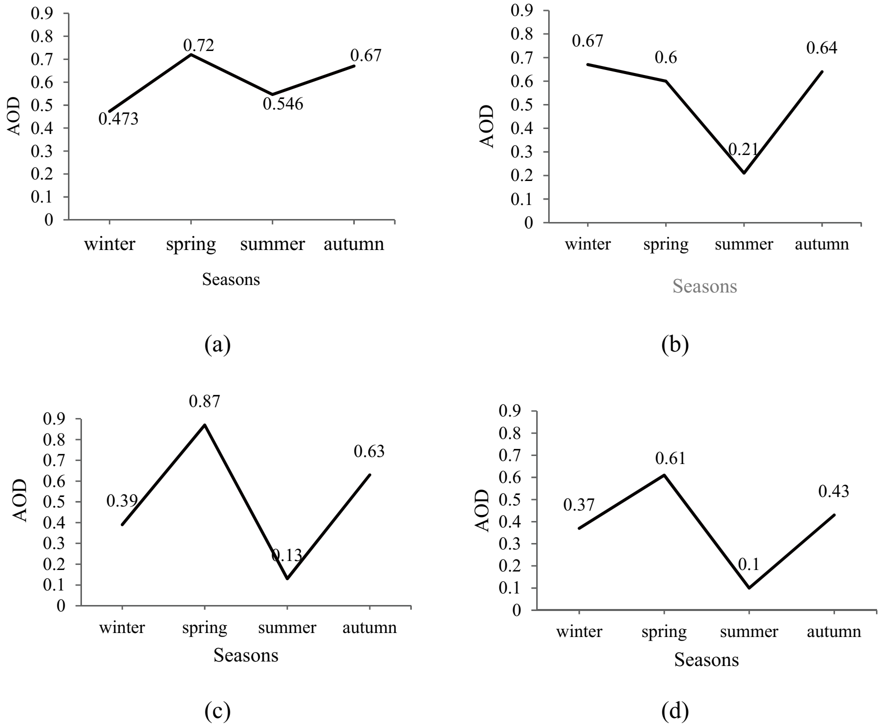

Fig. 14 Seasonal variability of AOD in (**a**) Western Indo-Gangetic Plain, (**b**) Central Indo-Gangetic Plain, (**c**) Part of Northeast and western Myanmar region and (**d**) Central and Eastern Region of India

in India, +0.79% in Myanmar, +3.86% in Pakistan, and +1.66% in Sri Lanka annually. Correspondingly, there has been a rise in average Aerosol Optical Depth (AOD) during the same period: +3.20% in India, +0.33% in Pakistan, 0.22% in Afghanistan, and 4.36% in Bangladesh per year. Through extensive observation, four distinct hotspot zones have been identified: the western Indo-Gangetic Plain (IGP), central IGP, Parts of North-East India and Western Myanmar, and the Central-Eastern region of India. Analysis of seasonal variations in fire occurrences and AOD reveals a significant correlation: as fire frequency increases in these hotspots, there is a corresponding rise in aerosol loading. This suggests that a substantial portion of atmospheric aerosol loading can be attributed to emissions from these fires.

This insight provided a comprehensive understanding of the region's spatial and temporal distribution of aerosols and fire hotspot zones. The results emphasized the interplay between fire activities and aerosol concentrations. The observed increase in fire incidents and degrading air quality due to aerosol loading highlights the critical need from the countries for efficient fire management techniques and efficient policies and regulations to curb air pollution throughout South Asia. Since wildfires and air pollution represent enormous hazards to ecosystems, human health and socioeconomic activity, it is critical to establish comprehensive fire prevention, early detection and response strategies and effective policies and action plans to control air pollution.

Acknowledgements The authors gratefully acknowledge The Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center (LAADS DAAC) (https://ladsweb.modaps.eosdis.nasa.gov/) for providing SNPP-VIIRS, Aerosol Optical Depth Data Products and also we acknowledge the use of data and/or imagery from NASA's Fire Information for Resource Management System (FIRMS) (https://earthdata.nasa.gov/firms), part of NASA's Earth Observing System Data and Information System (EOSDIS) for providing SNPP-VIIRS, Active fire points data products that is used in this study.

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Mapping and Monitoring of Asan Watershed Using Geospatial Technology

Joselyn B. C. Toomey, Rachan Karmakar, Suman Naithani, and Pratibha Naithani

1 Introduction

Water is a significant source of renewable energy, necessary for life, and crucial for environmental health (Brown et al., 2005; Park and Kim, 2019; Boelee et al., 2019; Eren and Akyuz, 2020; Lalawmpuii and Rai, 2023; Panwar et al., 2011; Panagopoulos, 2021; Hanjra et al., 2012; Borella et al., 2005; Madhav et al., 2020; Hyunwoong and Kim, 2019; Zhang et al., 2004). The burgeoning human population and pressures on natural resources exacerbate the over-exploitation and depletion of land and water resources. Contributing factors include unsustainable biophysical and management practices, poverty, high population density, agriculture, infrastructure development, limited market access, and governmental policies (Lambin et al., 2001; Datta, 2019; Chan et al., 2019; G. Water, n.d.; Wackernagel, 1994; Pathak and Pal, n.d.). The watershed serves as the catchment basin collecting water from various streams within an area and directing it towards a common outlet, delineating the boundary separating adjacent drainage basins (Colby et al., 2019; Li, 2019; WMO, 2012). Effective watershed management entails the development and implementation of strategies aimed at maintaining and enhancing watershed functions, delivering necessary commodities, services and values, influenced by its unique conditions (Floress et al., 2015).

J. B. C. Toomey (✉) · R. Karmakar · S. Naithani · P. Naithani
Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India
e-mail: rachan.in.air@gmail.com

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Geospatial technology has demonstrated effectiveness in water resource management, development and prioritization of watersheds, as evidenced by researchers' utilization for efficient and effective initiatives (Chakraborty et al., 2001; Chowdary et al., 2013). Remote sensing (RS) gathers data on Earth's surface from satellites, aircraft or drones, offering reliable and updated information on topography, natural resources, and physical features, ensuring accuracy and timeliness (Choi et al., 2005). Geographical Information System (GIS) serves as a potent tool for capturing, storing, analysing and visualizing geographical data, facilitating the efficient management of complex databases and watershed development zones (Gosain and Rao, 2004). This environmentally conscious approach involves the prudent utilization of natural resources and engaging institutions, organizations and communities (Purvis et al., 2019; Lertzman and Vredenburg, 2005; Liu et al., 2009; Zia et al., 2021; Basiago, 1998; Camilleri, 2017; Roseland, 2000; Gardner, 1989; Yadav et al., 2022; Jhariya et al., 2021; Fujitan et al., 2020; Lockie and Sonnenfeld, 2008).

Watershed development programmes have grappled with inadequate databases on numerous planning criteria and a lack of research on techniques and execution (Dhruva Narayana et al., 1970; Sarkar & Singh, 1997; Vaidyanathan et al., 1991). Mishra et al. (2023) analysed the impact of integrated watershed development programmes on dry land farming in three districts of Orissa, revealing a positive change in cropping patterns, with a shift from traditional crops to more valuable cash crops. Palanisami and Suresh Kumar (2009) assessed the impact of the Drought Prone Area Programme (DPAP) watershed in Coimbatore, noting significant improvements in groundwater recharge, access to groundwater and the expansion of irrigated areas. Palanisami and Kumar (2009) analysed the performance of 525 farm households in Coimbatore in 2003, emphasizing the efficacy of geospatial technology in identifying priority areas for conservation within watersheds (Bhalla et al., 2011; Singh et al., 2023). By overlaying spatial layers, including biodiversity hotspots, water quality data and land use patterns, researchers can pinpoint areas requiring immediate attention. However, challenges persist in data collection for watershed assessment due to insufficient site-specific data and continuity issues, leading to repeated work and difficulties in correlating data.

1.1 Study Area

The Asan watershed, a vast intermontane valley situated in the western half of the Doon Valley, serves as a research area covering 784.36 square kilometres (sq.km). Its primary streams flow into the Yamuna River, and it experiences a humid subtropical monsoon climate with an annual rainfall of 2200 mm. The research region spans between 77°38′05″ and 78°05′50″ East Longitude and 30°14′15″ North to 30°30′51″ North Latitude. Figure 1 illustrates the map of the study area. This study assessed changes in land use and land cover using geospatial methods, delineates the drainage of the Asan watershed using Digital Elevation Model (DEM), and calculates slope and aspect using DEM data.

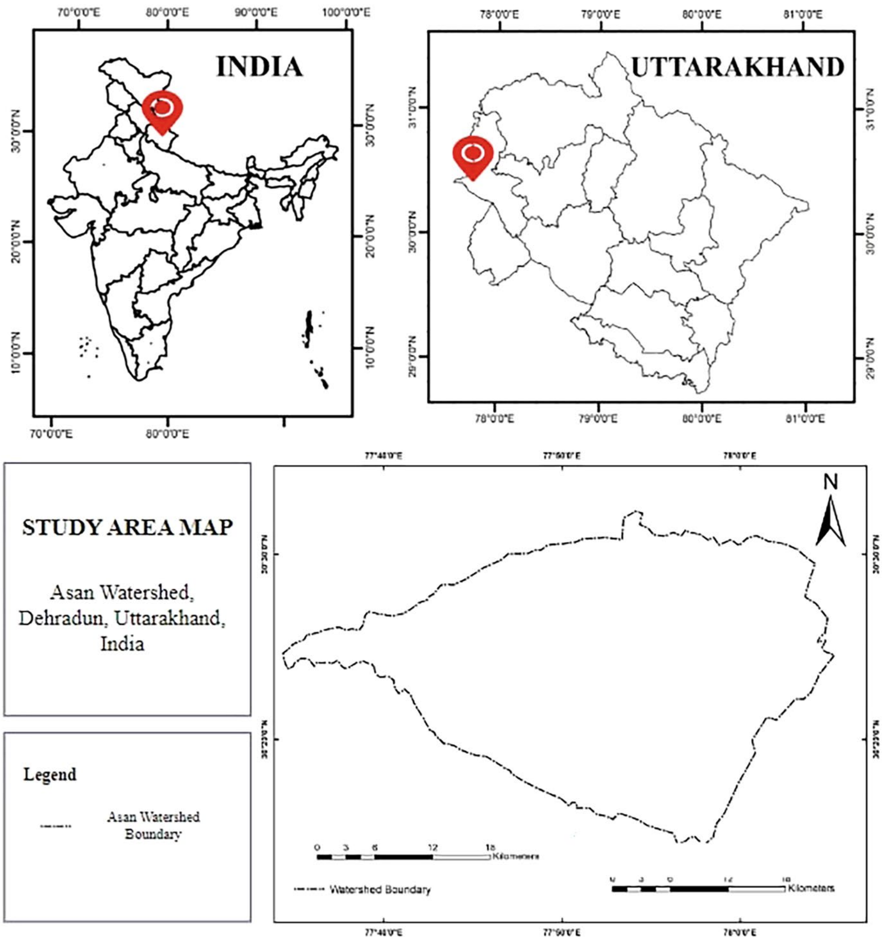

Fig. 1 Study area map

2 Materials and Methods

2.1 Classification and Mapping of LULC

The assessment of terrain involving the analyses of various thematic layers such as geology, geomorphology, structure, drainage, and land use/land cover was conducted using data obtained from the United States Geological Survey (USGS), a freely available satellite imaging system. This data was processed through visual analysis of satellite imagery combined with accessible ancillary data and previous research efforts. Figure 2 illustrates the emphasis on identifying variations in terrain through satellite imagery and anthropological data. A quantifiable system of variation was employed in this study, with each satellite image analysed using a change analysis approach. The study utilized several approaches, including dataset collection, pre-processing, and digitization using Geographic Information System (GIS) software (ArcGIS, version 10.3), categorization of land use and land Cover (LULC), and image classification.

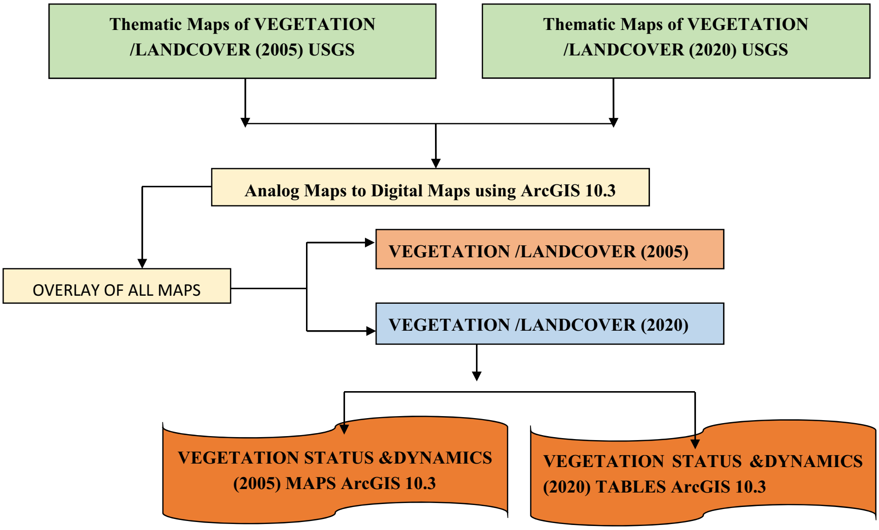

Fig. 2 Process of evaluating land use and land cover of the study area for developing tables and maps

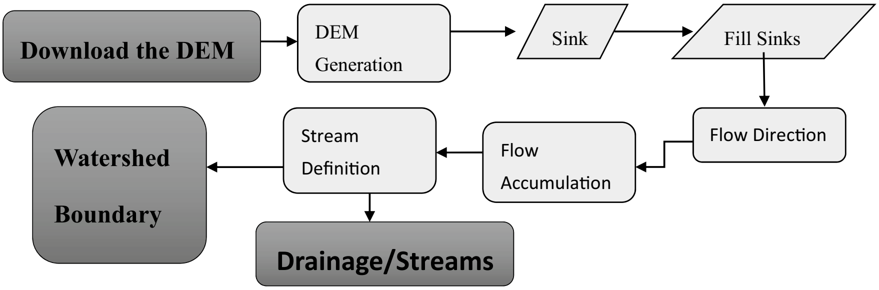

Fig. 3 Flow chart generation of drainage using digital elevation model

2.2 Preparation of Drainage from DEM

To delineate irrigation potential zones, various thematic maps were created using data from remote sensing, topographic maps, geological maps, reports and other sources. In Fig. 3, thematic maps were generated from data obtained from the Indian Remote Sensing-1D (IRS-1D), Linear Image Self Processing System III (LISS-III) sensor, Sentinel-22,020 data, and the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) use to generate Digital Elevation Model (DEM). These datasets were processed using ArcGIS software, along with topographic maps and ancillary data, to develop fundamental thematic layers within the GIS environment.

Table 1 LULC categories of changes in 2005 and 2020 data sets, as well as fluctuation in each class's scope over 15 years (in km^2)

S. no	Land use/land cover (LULC)	Area in (Sq.km) 2005	Area in (Sq.km) 2020
1	Agricultural land	124.31	117.42
2	Agricultural plantation	8.83	13.49
3	Built-up	9.71	17.87
4	Forest	183.37	181.23
5	Forest plantation	0.56	2.26
6	Wastelands	5.52	6.95
7	Water bodies-canal	0.89	0.78
8	Water bodies-reservoir/tanks	0.68	0.67
9	Water bodies-river/stream-dry	27.98	20.36

Table 2 LULC categories changes matrix from 2005 to 2020 scope in percentage

S. no	Land use/land cover class of 2005	Land use class of 2020	2005%	2020%
1	Agricultural land	Agricultural land	34.35	32.45
2	Agricultural plantation	Agricultural plantation	2.44	3.73
3	Built-up	Built-up	2.68	4.94
4	Forest	Forest	50.67	50.08
5	Forest plantation	Forest plantation	0.15	0.62
6	Wastelands	Wastelands	1.52	1.92
7	Water bodies-canal	Water bodies-canal	0.24	0.22
8	Water bodies-reservoir/tanks	Water bodies-reservoir/tanks	0.18	0.19
9	Water bodies-river/stream-dry	Water bodies-river/stream-dry	7.73	5.63

3 Results and Discussion

3.1 Statistical Interpretation of Land Use and Land Cover (LULC) Changes Detected from 2005 to 2020

Over the course of 15 years in the region covered by the LULC classifications, uplifted and downlifted deviations were studied as shown in Tables 1 and 2. The aquatic portion, forestry and farming land set all showed a decrease in zone size; however, the built-up grew in size. The greatest extent of changes was seen in the urban/other terrain classes followed by water bodies, agronomy land, and forestry.

3.2 LULU Map Analysis

The highest and lowest elevations in the area were determined to be 2221 and 262 m, respectively (see Figs. 4 and 5). A Land Use, Land Cover (LULC) classification was conducted using the Uttarakhand Space Application Center (USAC) License version of ArcGIS software in analysing changes within the watershed's land use patterns a 15 years period, from 2005 to 2020. The study revealed a decrease in water bodies of approximately 2.10% with a rise of approximately

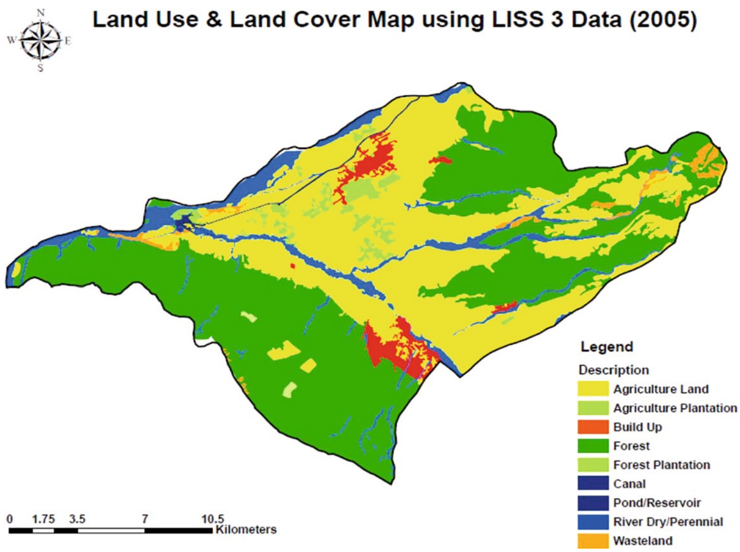

Fig. 4 Land use, land cover for the year 2005

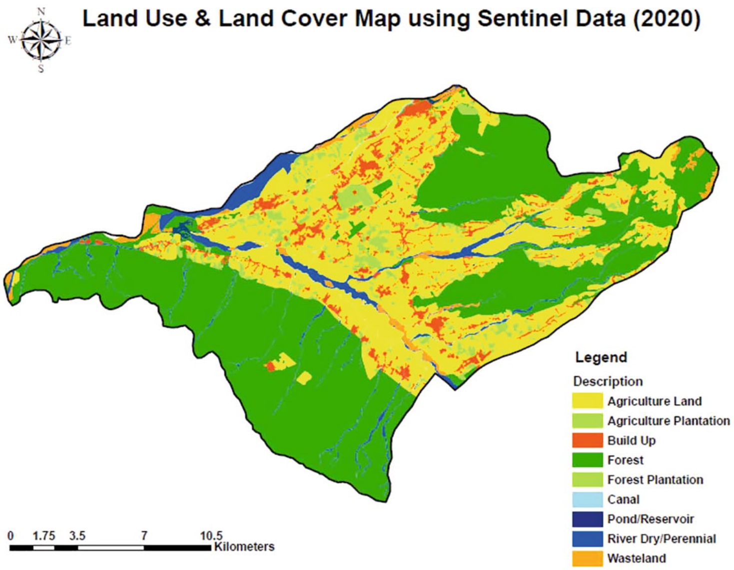

Fig. 5 Land use, land cover for the year 2020

2.25% in the expansion of developed regions. Satellite imagery from 2020 indicates that farmers are increasingly focusing on agricultural plantations rather than traditional crops.

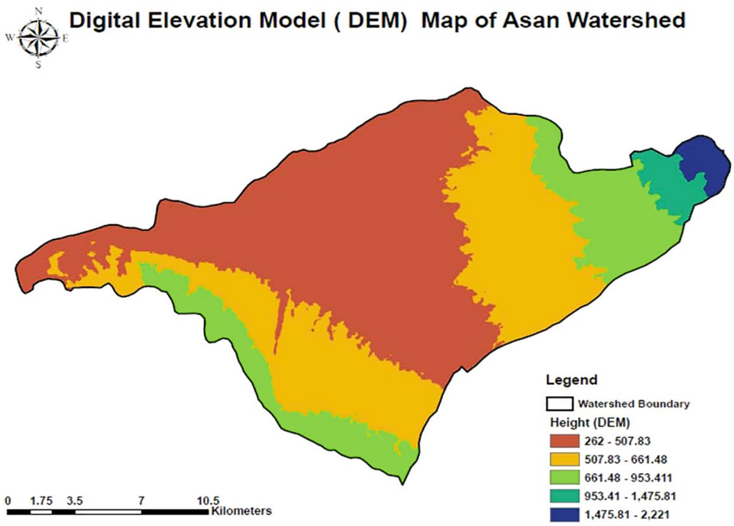

Fig. 6 Digital elevation model (DEM ASTER 30 m)

3.3 Digital Elevation Model (DEM ASTER 30 m)

The Digital Elevation Model (DEM) is used to represent the elevation of a particular area. By creating a colour composite shadow map that is transparent, the terrain of the study area can be clearly seen. Additionally, a drainage network can be constructed on top of the existing levels. Before utilizing the flow direction technique, it is important to clean up the DEM by removing local depression sinks. This can be done using the Fill Sinks procedure, which removes depressions from the DEM. The Asan watershed boundary height refers to the elevation values of the terrain along the edges or boundaries of the watershed area. This includes the highest and lowest elevations along the perimeter of the watershed. In Fig. 6, the first range, 262 m suggests that the highest point in the watershed is around **262** units of elevation, while 2222 m, suggests that the lowest point in the watershed is around **2222** units of elevation.

3.4 Flow Direction/Accumulation for Drainage Generation

In Fig. 7, the operation determines the direction in which water within the centre of a pixel will naturally flow. The flow direction of each central pixel in the three-by-three-pixel input block is calculated by comparing its value to the values of its eight neighbours. The created map shows flow directions as N (North), NE (Northeast), and so forth. The flow accumulation operation constitutes a cumulative count of the number of pixels that gradually drain into outlets, offering insight into drainage pattern of a terrain. This operation utilizes the output map from the procedures of flow

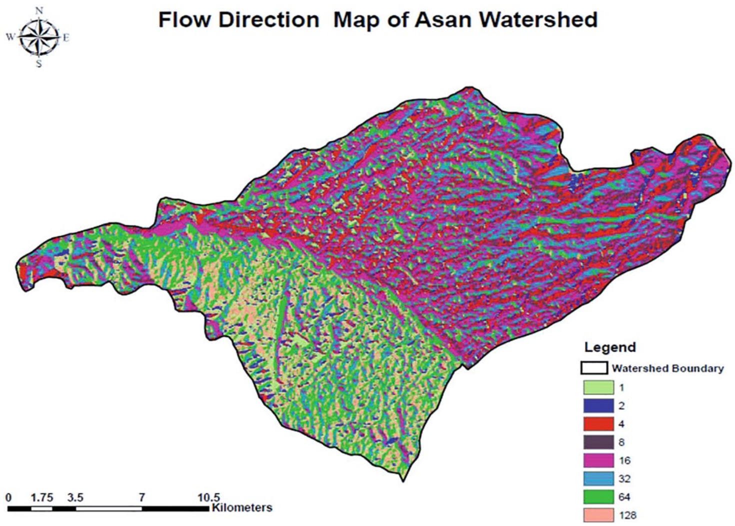

Fig. 7 Flow direction/accumulation map of Asan watershed

direction as input, providing total hydrological values of flow that denote the amount of input pixels contributing water to the outlets, with larger values indicating outlets of significant streams or rivers.

Flow modification DEM optimization enhances a Digital Elevation Model (DEM) by incorporating existing drainage features into it. This ensures that subsequent operations, such as flow direction, follow the existing drainage pattern.

Topological optimization addresses undefined values in a DEM or flow direction map, such as those caused by lakes in the study area. This operation improves the results of previous operations by connecting drainages through lake areas. Multiple passes of this operation may be necessary, with each pass using the output of the previous pass as input, to ensure proper flow connectivity.

3.5 Drainage Extraction, the Drainage Network

The extraction method distinguishes a basic drainage network by generating a Boolean raster map where pixels representing basic drainage paths are marked as true, while others are marked as False. This process requires the flow accumulation output raster map as an input, which represents the combined drainage counts of each pixel. Drainage network ordering entails inspecting all drainage lines in the network map generated by the drainage network extraction process. It finds nodes where many streams merge and assign a unique ID to each segment between these nodes, as well as streams that have only one node. The output includes raster and segment maps, along with attribute data utilizing a newly created ID domain.

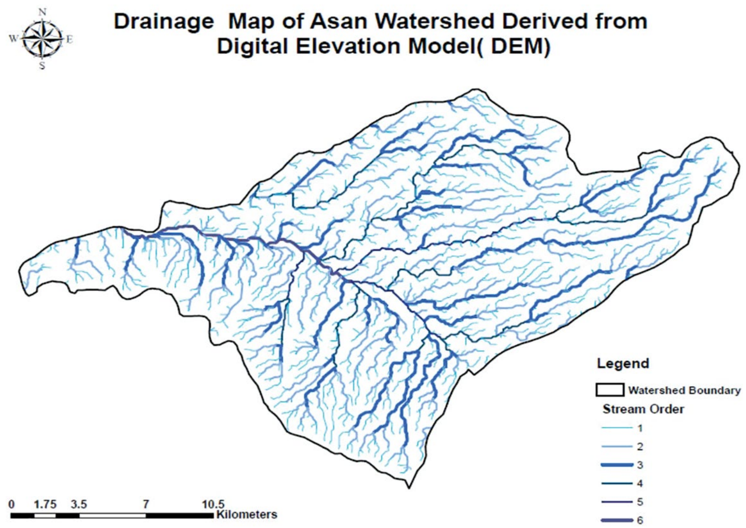

Fig. 8 Drainage map of Asan watershed

The DEM effectively delineated topographic variations in elevation across the study area, which exhibited a wide range from 262 to 2221 m. The stream network's configuration reflects the underlying structural arrangement of rocks, where bends in the streams indicate the presence of hard or soft rock formations influencing water flow, akin to the interconnected pathways of a neural network in the human body.

The stream order depicted in Fig. 8 is dendrite, indicating the hierarchical classification of streams and rivers within the drainage basin, illustrating the number of tributaries contributing to the main river or stream.

In stream hierarchy, a first-order stream is a tiny, branched-out stream that has no tributaries. When two first-order streams merge, a second-order stream emerges. Similarly, the convergence of two second-order streams results in a third-order stream, and the process continues. A sixth-order stream represents a larger river formed by the confluence of multiple fifth-order streams.

3.6 Slope of the Study Area

Using the generated DEM, the slope of the two study blocks was calculated using ArcGIS 10.3's surface tool. In terrain analysis, slope refers to the angle at which a physical feature or topographic landform is inclined relative to the horizontal surface. It is an important parameter in morphometric research because slope elements are modified by climatic and morphogenic processes, especially in places where rocks have varied resistance. The slope is calculated by measuring the angle between

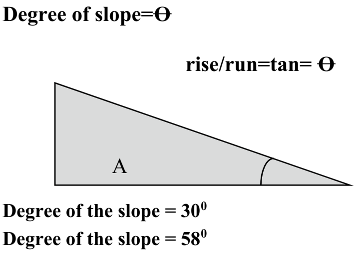

Fig. 9 Formula for delineating the slope

the topographic surface and a reference datum. Both planar and geodesic computations take place within a three-by-three cell neighbourhood. If the centre cell in each neighbourhood is No Data, the output is labelled as "No Data."

Slope aspect is a vital factor affecting plant growth and cultivation. It influences temperature and humidity variations on slopes facing different directions: those directly facing the sun, those partially facing the sun, and those not facing the sun at all. Aspect categories are represented using hues, and classes of slope degrees are depicted with varying saturation levels to highlight steeper slopes. Aspect maps are generated using ASTER DEM data at a resolution of 30 m.

It has been noticed that the steeper the surface, the greater the slope, which is quantified by computing the surface's tangent. This tangent is calculated by dividing the vertical change in elevation by the horizontal distance. When looking at the surface in cross-section, right-angled triangle visualization can help demonstrate this computation. Figure 9 presents a diagram illustrating the formula for slope delineation.

The slope is typically given in planning as a percentage slope, which is the tangent slope multiplied by 100. This method of expressing slope is widespread; however, it might be confusing because 100% slope is a 45-degree angle because the height and base of a 45-degree angle are identical, and when divided, always equal 1 and multiplied by 100 equals 100%. In reality, as the gradient approaches a vertical surface (the base distance approaches zero), the slope per cent will probably reach infinite. In practice, this is impossible in a gridded database since the base is never less than the width of a cell. **Percent Slope = (Height/Base) * 100.**

Slope is separated into five categories, each with its own weight. Ages and weights were assigned based on the slope aspect. A slope of less than 10 is considered a plain region because little runoff is typically a favourable recharge zone. Because of their modestly undulating topography and little runoff, sites with 1–20 slopes are thought to be ideal for groundwater storage. Areas with a slope of 2–30 create relatively moderate runoff, and so are classified as moderate. Slopes ranging from 4 to 50 are almost regarded poor, while slopes greater than 50 are considered very poor due to the higher slope and quick runoff as shown in Fig. 10. In the

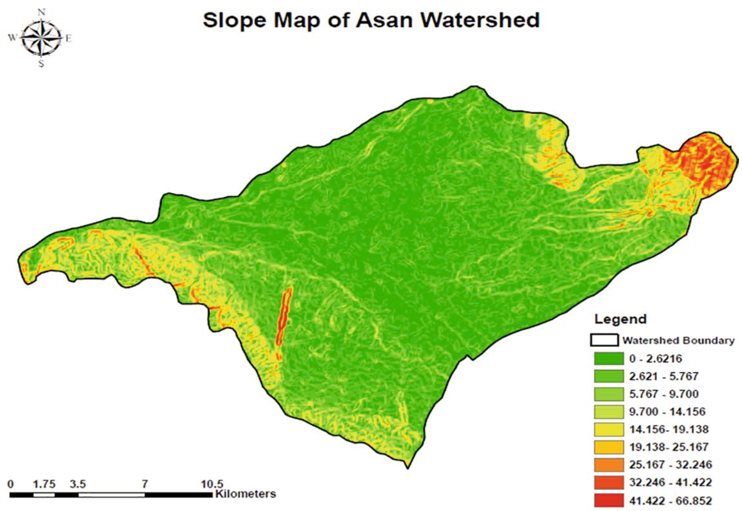

Fig. 10 Slope map of Asan watershed

development of the irrigation potential map, severe dips of beds are given the least weightage, while gentle slopes are given more weightage since slope plays an important role in infiltration versus runoff. Soils with a high water-holding capacity, such as sandy clay, have been given a higher weightage.

3.7 Aspect of the Study Area

Aspect is determined by calculating the north-south and east-west gradients. This parameter holds significant importance for plant growth and cultivation as it influences temperature and humidity variations across slopes. Slopes can be categorized into three types based on aspect: those directly face the sun, those partially facing the sun, and those not facing the sun at all. Aspect categories are represented using different hues, while classes of slope degrees are depicted with varying saturation levels to highlight steeper slopes. Aspect maps are generated using ASTER DEM data with a resolution of 30 m. The aspect's compass direction is calculated from the output raster data, where 0° represents true north, 90° refers to an eastward direction, and so on. The region studied has predominantly eastward-flowing slopes with higher moisture and lower evaporation rates, as indicated in Fig. 11, leading to a higher vegetation index.

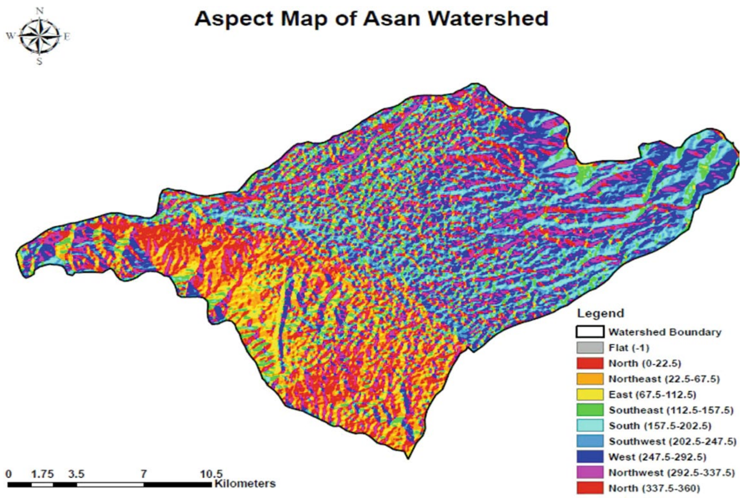

Fig. 11 Aspect map of Asan watershed

4 Conclusion

The Asan watershed and its catchment display a diverse topography, as evidenced by DEM analysis indicating relatively low relief with basins less than 262 m in elevation. Surface processes are primarily influenced by altitude, slope, rainfall, soil characteristics, geography and geology. The drainage system of the Asan watershed exhibits a dendrite pattern, representing a sixth-order stream according to Strahler's method. The area of study is predominantly characterized by agricultural land along with forested areas. Forested land constituted the highest percentage in both satellite images from 2005 and 2020, while agriculture, water bodies, and wasteland classes showed a decrease in total area, and built-up land exhibited an increase.

The area under water and forest decreased from 2005 to 2020, while the area under built-up land saw the highest increase of 2.95% during the same period. Much of the agricultural land in the Asan watershed has been converted to built-up land, indicating encroachment and the shrinking of forested and agricultural areas. Factors contributing to watershed degradation include weed infestation, changes in watershed hydrology and soil erosion deposition.

Hydrological research indicates a very low relief in the watershed, with a dendritic drainage network structure indicating consistent structural control and assisting in the study of various topographical characteristics such as infiltration capacity, bedrock composition and runoff. The results are compiled to identify areas for surface-water recharge and augmentation solutions for water and soil management. Watershed analysis, combining DEM, GIS and remote sensing data, aids in improved groundwater management, drainage management and landform processes prospective for watershed management and planning.

The research findings can inform the long-term development and administration of available natural resources at a small scale, highlighting the need for hydro geological and geophysical investigations for correct water management and simulated revitalization of groundwater configurations. GIS technology has proven highly useful for slope and DEM analysis, impact analysis of water management interventions, and multi-temporal satellite data analysis for capturing dynamic phenomena such as land use change. It facilitates spatial and non-spatial data handling; runoff and sediment yield modelling, and ultimately saves time and manpower compared to conventional methods.

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Drought Vulnerability Assessment of Farming Communities in the North Central Province of Sri Lanka: A Community Capital Framework Analysis

L. M. A. P. Gunawardhana, L. M. Dharmasiri, and M. M. Ranagalage

1 Introduction

Drought is one of the most complex, slow onset and least understood natural hazards (Alamgir et al., 2019; Badripour, 2007; Fu et al., 2013; Gebrehiwot & van der Veen, 2015; Hayes et al., 2004; Jin et al., 2016; Keshavarz & Karami, 2016; Rey et al., 2017; Skakun et al., 2016; Valverde-Arias et al., 2018; Wilmer & Fernández-Giménez, 2015). Drought can occur due to both natural causes such as El Nino and La Nina, low rainfall, global warming, etc., and human activities such as urbanization, construction, deforestation, etc. However, drought is basically a recurrent feature of the climate and the frequency of drought has increased due to rapid climate change ongoing throughout the world (Hao et al., 2012; IPCC, 2007, 2014; Kalisa et al., 2021; Kamali et al., 2019; Raksapatcharawong & Veerakachen, 2019; Wickramasinghe et al., 2021; Wilhite, 2021; Yildirim et al., 2022). It is unable to find a universally accepted definition of drought because drought is defined differently in different countries and regions of the world, considering the drought

L. M. A. P. Gunawardhana (✉)
Faculty of Graduate Studies, University of Kelaniya, Kelaniya, Sri Lanka

Department of Environmental Management, Faculty of Social Sciences and Humanities, Rajarata University of Sri Lanka, Mihintale, Sri Lanka
e-mail: gunawardhanap@ssh.rjt.ac.lk

L. M. Dharmasiri
Department of Geography, Faculty of Social Sciences, University of Kelaniya, Kelaniya, Sri Lanka

M. M. Ranagalage
Department of Environmental Management, Faculty of Social Sciences and Humanities, Rajarata University of Sri Lanka, Mihintale, Sri Lanka

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phenomenon and its impacts in their socioeconomic and environmental context (Wilhite, 2021; Wilhite & Glantz, 1985). In general, drought is a deficiency of precipitation from expected or normal over an extended period for a season or long period in an area (Badripour, 2007; Bokal et al., 2014). Broadly, drought can be defined conceptually and operationally (Kchouk et al., 2021; Wilhite & Glantz, 2019). Drought is different from other environmental hazards, such as floods, cyclones, landslides, tsunamis, etc., due to inherent characteristics. First, the effects of drought slowly accumulate over considerable time, and anyone cannot predict the commencement and end like cancer. Second, there is no globally accepted definition for drought, and third, the impacts of drought are non-structural spread over a larger area from local to region, creating uncountable damages for many sectors (DeChano-Cook, 2018; Smith, 2013; Tennakoon, 1986; Wilhite, 2021).

Though there are several drought types, most researchers have accepted four types of drought categories: meteorological, agricultural, hydrological, and socioeconomics or famine (Hagenlocher et al., 2019; Raksapatcharawong & Veerakachen, 2019; Wilhite & Glantz, 2019). Meteorological or climatological drought is measured based on precipitation received in an area, and the amount of rainfall differs from region to region, so it is typically considered a deviation from normal rainfall in an area. Agricultural drought is linked with meteorological drought because when rainfall is not received, it will lead to a reduction in the soil moisture for crops, and water is needed for crop growth at the different stages; when deficiency of soil moisture will lose the growth of the crops and finally damage to harvest so, agricultural drought is identified deficiency of the moisture level of the soil. Hydrological drought is measured through the deficiency of surface water bodies such as rivers, tanks, streams, and underground water levels such as wells, tubes, wells, etc. Hydrological drought is also linked with both meteorological and agricultural drought because a lack of rainfall in an area leads to create competition among water users for different purposes such as agriculture, industry, electricity, and other domestic activities. Finally, all three types of drought lead to socioeconomic or famine drought. Socioeconomic drought is measured through the space created between the supply and demand of some goods or services (Hagenlocher et al., 2019; Wilhite, 2021; Wilhite & Glantz, 2019). Drought creates many socioeconomic and environmental losses, particularly in developing countries (Chengot et al., 2021; Etemadi & Karami, 2016; Rey et al., 2017; Smith, 2013). According to the World Health Organization (2023), it is estimated that around 55 million people are globally affected by drought every year and around 700 million people will suffer due to lack of water by 2030. Drought vulnerability assessment is an essential component of drought risk assessment because drought risk is the combined effects of drought hazard and vulnerability (Birkmann, 2013; Heydari Alamdarloo et al., 2020; Jia et al., 2012). The simple meaning of vulnerability is the possibility of being attacked or harmed due to some hazard (Wilhelmi & Wilhite, 2002). The concept of vulnerability is linked with many subjects, and it has multi-dimensions such as social, economic, environmental, political, cultural, etc. (Etemadi & Karami, 2016; Wisner, 2015). Most researchers have pointed out that vulnerability assessment should be composed of its significant components of exposure, sensitivity, and adaptive capacity (Mohmmed et al., 2018). Various researchers have introduced various tools and indexes to assess drought vulnerability, but they cover limited variables, most of the time economic, social, and environmental factors. The Community Capital Framework (CCF) proposed by Flora and Flora (2007) includes a more comprehensive range of factors, and it is the most effective tool for assessing social vulnerability (Jordaan et al., 2018). Seven capitals are included in CCF: natural, cultural, human, social, political, financial, and physical (Anglin et al., 2014; Anglin, 2015; Emery & Flora, 2020; Gordillo & Santana, 2019).

Sri Lanka has undergone drought for a long history, and severe drought has been occurring in every century (Siriweera, 1987). Drought has been identified as a major disaster in the Sri Lanka Disaster Management Act No. 13th of 2005 (Amaraweera et al., 2018; Gunawardhana & Dharmasiri, 2015). Sri Lanka is an agricultural country, and many challenges have been faced since ancient times. That is why the ancient kings of Sri Lanka have built over 30,000 small and large tanks in a cascade setting (Madduma Bandara, 2009). Farming communities in Sri Lanka are more vulnerable to drought than other communities because nearly 72% of Sri Lankans practice agriculture as their primary livelihood (De Costa, 2010). A plethora of research has been conducted in Sri Lanka on drought since the early nineteenth century, and their main objectives were to identify the drought occurrence, impacts, perception of people, adaptation, and mitigation strategies (Bandara, 1983; Dharmasena, 2004; Tennakoon, 1986). However, research on drought assessment is minimal, but it is essential to drought risk assessment and management. Hence, the major objective of this research was to apply CCF for assessing drought vulnerability among farming communities of the North Central Province (NCP) of Sri Lanka. Specific objectives of this research were to find different vulnerability levels of three selected farming communities, i.e., Mahawilachchiya, Kahatagasdigiliya, and Medirigiriya, in the NCP in terms of different capitals of the CCF and analyze selected individual capital vulnerability among the farming communities in the NCP.

2 Methods

Sri Lanka is one of the islands with a total land area of 65,610 km^2 with a nearly 22.6 million population by 2021. It is situated in the Indian Ocean near the southern parts of the Indian continent between 5°-55′-9°5′ North latitudes and 79°42′-81°-53′ East longitudes (Eeswaran et al., 2018). Sri Lanka is divided into 9 provinces and 25 administrative districts. Climatologically, it is divided into 3 zones based on annual average rainfall: dry zone (<1750 mm), intermediate zone (1750–2500 mm), and wetzone (>2500 mm) (Manawadu & Fernando, 2008). This study was carried out in the North Central Province (NCP), which is most vulnerable to drought, and the whole land area (10,472 km^2) is situated in the Dry Zone. NCP is the largest province in terms of land area and is divided into 2 districts, Anuradhapura and Polonnaruwa, and 29 Divisional Secretariat Divisions (DSD). NCP provides home to nearly 1.2 million people, and the majority are farmers (see Fig. 1). Three DSDs, namely Mahawillachhciya, Kahatagasdigiliya, and Medirigiriya, were selected

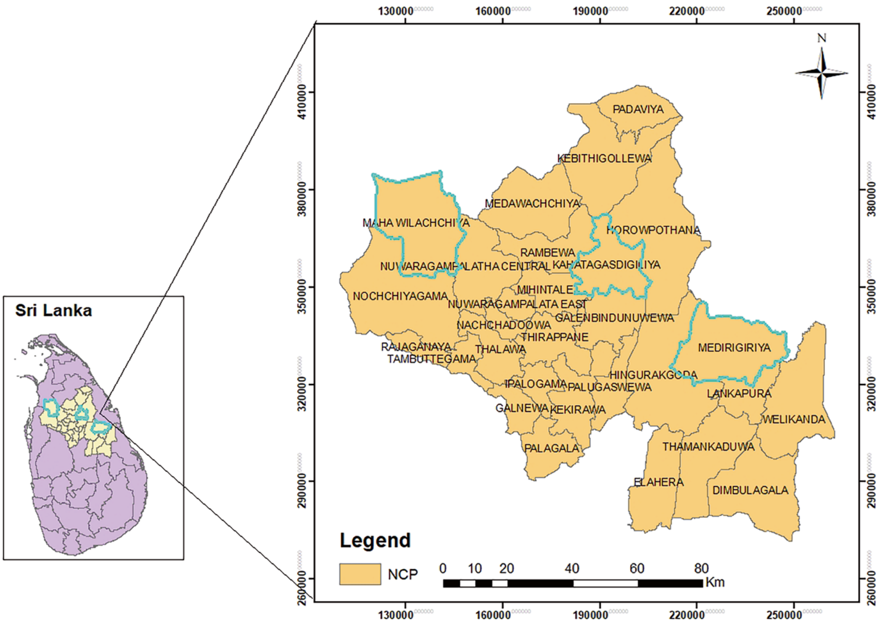

Fig. 1 Study area (North Central Province Sri Lanka (NCP))

based on the literature review and rainfall distribution pattern of the NCP. The mixed method was adapted for this research, where both qualitative and quantitative data were collected using a structured questionnaire and field observation. The statistically significant sample size was determined using Slovin's formula. Accordingly, 356 samples from farming households were selected using the stratified random sample method. Geographical areas were considered as the strata. The total sample was obtained from three selected DSDs proportionately to the total farming families of each DSD. Researchers upgraded the CCF, adding two capitals as spiritual and technological capitals to the seven capitals proposed by Flora and Flora (2007) after a literature review (see Table 1).

The questionnaire was designed to measure each capital through various sub-variables proposed by previous researchers in a manner that captures the basic meaning of each capital, and the questionnaire was validated by a panel of experts. The field survey was conducted using face-to-face interviews from January to March 2023. Responses were collected as Yes and No answers, then converted into 0–1 as No = 0, Yes = 1, and calculated the average of the unweighted sum of the variables representing each capital, which represents the capital index values proposed by Bennett (2012) as very high vulnerability (0–0.25), high vulnerability (>0.25 to 0.5), medium vulnerability (>0.5 to 0.75), and low vulnerability (>0.75 to 1). The Kruskal-Wallis Test was performed using the Statistical Package for Social Sciences (SPSS) to identify the significance of the variations of capitals among the selected three communities. The study area map was created by the researcher using

Table 1 Defining the nine selected Capitals of the Community Capital Framework (CCF)

Capitals CCF	Definition
Human capital	Qualities of individuals that enable to earn a living, strengthen the community, contribute the community organization, their families and self-improvement e.g.: education, health, personal skills etc.
Cultural capital	Qualities gained from family, school, and community such as values, norms, beliefs, and traditions as well as material goods produced at a specific time and place that have cultural and historical significance
Social capital	Linkage or connection which have among people and organization will help achieve a collective community vision
Political capital	The ability of people access to political powers and influence on policy making, enforce rules, and standards and participate on significant public crisis
Natural capital	The total number of resources existing in a community items of both quality and quantity such as parks, mountains, water, land, river, etc.
Built capital	The basic set of facilities, needed by the community such as services, physical structures, roads, hospitals, transpotations etc.
Financial capital	Monetary resources such as access to bank, loans etc.
Spiritual capital	Religious belief, practices of a person which will influence on social development
Technological capital	Technology is defined in a different context here the general meaning is that man's creations such as the internet, machines, new methods, and strategies etc.

Source: Compiled based on Anglin et al. (2014) and Saxena et al. (2020)

ArcMap 10.8 software using the data collected from the Survey Department of Sri Lanka and all other tables and figures were composed by the author using MS Excel 2013 version where data collected from the field survey was utilized. The results were presented as mainly text, graphs, tables, and figures.

3 Results

Before discussing the results of the study, it is essential to analyze the significant characteristics of the sample profile selected for this study. Purposively, sample frames were selected concerning the farming community of the NCP. Mainly, farmers in the NCP can be divided into four groups: major irrigation, medium irrigation, minor irrigation, and rain-fed farmers. Previous research findings have pointed out that minor irrigation and rain-fed farmers are the most vulnerable group related to drought hazards in the NCP. Therefore, the whole sample has been drawn from minor and rain-fed farmers who are living in three different DSDs, namely Mahawilachchiya, Kahatagasdigiliya, and Medirigiriya. As rice is the staple food in Sri Lanka, traditionally, farmers grow rice in *Maha* (October to March) and *Yala* season (April to September). Most of the time, the *Yala* season is not successful for minor and rain-fed farmers due to a deficiency of water caused by dry or drought conditions in the NCP. Though some group of farmers was selected from three different DSDs, it was found that there are some differences in practicing agriculture. Farmers in the Mahawilachchiya give their priority to chena or slash-and-burn cultivation rather than rice cultivation. Farmers in the Kahatagsdigiliya practice both rice and chena cultivation but give priority to rice cultivation rather than chena. Farmers in Medirigiriya give their priority to rice cultivation in both the *Maha* and *Yala* seasons.

When analyzing the age groups of the sample, the majority belong to the age group of 50–59 (28.1%). The lowest group is the 20–29 (6.2%). Most of the farming families' heads are males (90.2%), while family size ranges from 1 to 6, and the majority belong to family size 4 (32.3%). The education level of the farmers ranges from no schooling to graduation, but the majority belong to grades 6–11 (39.61%). The family's monthly income ranges from 20,000 rupees to 98,000, but the majority belongs to the 30,000–39,000 (19.1%), and the average family expenditure is 53,503.49 rupees; the majority portion of the income spent on food, education of the child, loan repayment and medicine respectively.

Vulnerability to the drought of the farming communities of the Mahawilachchiya, Kahatagasdigiliya, and Medirigirya areas of the NCP has been analyzed using CCF and the capital index. Three selected areas have been compared with nine capitals of the CCF. Table 2 shows the details of sub-variables selected for measuring the main capital and the capital values related to each sub-variable and major capital with reference to the Mahawilachchiya, Kanatagasdigiliya, and Medirigiriya. Table 3 describes the summary of the capital values and relevant vulnerability class related to each of the nine capitals for the three studied areas. Figure 2 illustrates how each capital varies among farming communities of Mahawilachchiya Kahatagasdigiliya and the Medirigiriya area of the NCP. Table 4 explains the statistical significance of the variation in community vulnerability in terms of selected nine capitals of CCF for three selected areas.

According to human capital, farming communities living in Mahawilachchiya, Kahatagasdigiliya, and Medirigiriya belong to very high vulnerability. There is a slight difference among the capital index values gained as 0.21, 0.19, and 0.18 Mahawilachchiya, Kahatagasdigiliya, and Medirigiriya, respectively; the variation is not significant ($P = 0.345$). This means that there is no significant variation of vulnerability among the three farming communities in terms of human capital (see Fig. 1). Human capital properties such as coping capacity to face drought, education level, health condition of the family, drought preparedness, and training on drought are very weak except for farmers' experience in agriculture for farming communities in the three areas. There is a slight change when comparing three areas in terms of cultural capital because 0.38, 0.39, and 0.41 in capital index values were received by the Mahawilachchiya, Kahatagasdigiliya, and Medirigiriya farming communities, respectively. However, there is no statistically significant variation ($P = 0.540$), and three areas belong to the high vulnerability category. However, there are variations among the sub-variables related to cultural variables (see Table 2).

When analyzing social capital for three areas, there is a significant change among the three studied communities ($P = 0.020$). Mahawilachchiya, Kahatagasdigiliya, and Medirigiriya have earned capital index values of 0.60, 0.53, and 0.60,

Table 2 Items evaluated for nine capitals in selected areas

Capitals	Items selected	Maha-wilachchiya	Kahatagasdigiliya	Medirigiriya
		Weighted values (Scale 0–1)		
Human Capital	Ability to face drought	0.08	0.06	0.06
	O/L passed farmers	0.06	0.13	0.09
	Kidney patients available in family	0.18	0.08	0.11
	Take some action before the drought	0.12	0.06	0.06
	Practice agriculture for more than 10 years	0.81	0.70	0.75
	Gain training on drought risk management	0.02	0.08	0.02
		0.21	**0.19**	**0.18**
Cultural Capital	Practice traditional festivals to avoid drought	0.38	0.60	0.59
	Ability to predict future drought	0.29	0.47	0.52
	There is a culture to prevent disasters	0.10	0.09	0.09
	Respect gender equality	0.80	0.65	0.75
	Participate in other religious festivals	0.13	0.20	0.17
	Practice traditional methods to control weeds and pests	0.56	0.35	0.35
		0.38	**0.39**	**0.41**
Social Capital	There is a membership in a farming organization	0.91	0.95	0.98
	There are sufficient organizations in the village	0.94	0.89	0.95
	Help from government institutions	0.23	0.17	0.24
	Help from non-government institutions	0.15	0.08	0.24
	There is a defense community in the village	0.78	0.60	0.69
	Family and friends support when facing drought	0.69	0.69	0.69
	Feel safe when going on the road at night	0.37	0.17	0.17
	There is satisfaction in the unity of the village	0.74	0.71	0.82
		0.60	**0.53**	**0.60**

(continued)

Table 2 (continued)

Capitals	Items selected	Maha-wilachchiya	Kahatagasdigiliya	Medirigiriya
		Weighted values (Scale 0–1)		
Political Capital	Satisfy with the drought preparedness	0.20	0.13	0.08
	Satisfy with the political relationship	0.10	0.08	0.06
	The government respects the community' proposals	0.08	0.09	0.08
	Receive help from politicians	0.03	0.02	0.05
	Satisfy with prices of crops approved	0.11	0.19	0.17
	Satisfy with agricultural policies	0.06	0.13	0.07
		0.10	**0.11**	**0.08**
Natural Capital	There is good soil for agriculture	0.74	0.68	0.84
	There is a good climate for agriculture	0.67	0.44	0.53
	There are enough water reserves for agriculture	0.15	0.05	0.04
	There are enough tanks (*Wewa)* in the area	0.38	0.68	0.65
	There are natural mountains in the area	0.07	0.01	0.01
	There are natural rivers in the area	0.02	0.01	0.02
	There is good biodiversity in the area	0.41	0.33	0.41
	There is enough forest cover in the area	0.24	0.43	0.60
		0.33	**0.33**	**0.39**

(continued)

Table 2 (continued)

Capitals	Items selected	Maha-wilachchiya	Kahatagasdigiliya	Medirigiriya
		Weighted values (Scale 0–1)		
Built Capital	There are sufficient school facilities	0.73	0.86	0.69
	There are sufficient hospital facilities	0.76	0.67	0.72
	There are sufficient electricity facilities	0.96	0.93	0.98
	There are sufficient transportation facilities	0.91	0.88	0.90
	There are sufficient communication facilities	0.81	0.86	0.86
	There are sufficient drinking water facilities	0.43	0.06	0.10
	There are sufficient market facilities	0.57	0.49	0.59
	There are sufficient irrigation facilities	0.38	0.20	0.24
	There are sufficient elephant fences	0.21	0.10	0.28
	There are enough agro wells in the area	0.37	0.17	0.22
		0.61	**0.52**	**0.56**
Financial Capital	There is an adequate income	0.33	0.33	0.32
	There is a functioning back account	0.87	0.81	0.86
	There are saved money	0.33	0.28	0.21
	There is crop insurance	0.12	0.08	0.03
	There is a life insurance	0.10	0.08	0.14
	There are off-farm income sources	0.33	0.23	0.24
	There is enough quality land for agriculture	0.47	0.50	0.67
		0.36	**0.33**	**0.35**
Spiritual Capital	There is access to religious institutions in the area	0.91	0.81	0.96
	Practicing religious activities when facing drought	0.77	0.72	0.87
	There is the ability to bear any loss	0.34	0.21	0.39
		0.67	**0.58**	**0.74**

(continued)

Table 2 (continued)

Capitals	Items selected	Maha-wilachchiya	Kahatagasdigiliya	Medirigiriya
		Weighted values (Scale 0–1)		
Technological Capital	Use drought-resistant crop varieties	0.42	0.24	0.45
	Changing cultivation according to water availability	0.52	0.53	0.56
	Get advice from an agricultural specialist	0.19	0.50	0.38
	Practice crop diversification	0.63	0.43	0.53
	Use the Internet for awareness of agricultural issues	0.03	0.05	0.02
	Use modern technology in agriculture	0.52	0.48	0.49
		0.38	**0.37**	**0.40**

respectively, in terms of social capital, and all three communities belong to the medium vulnerability category. There are some changes among the three communities in terms of sub-variables selected for measuring social capital. However, it was found that there is a low vulnerability related to some variables, such as respect for gender equality, relationship with their family, friends, village organizations, defense, and unity of the village. All farming communities in Mahawilachchiya (0.10), Kahatagasdigiliya (0.11), and Medirigiriya (0.08) belong to the very high vulnerability category, and there is no significant change ($P = 0.920$) in terms of the political capital among the three areas. There is a significant variation in vulnerability among the three farming communities in terms of natural capital ($P = 0.044$), and all three selected areas belong to the high vulnerability class.

Built capital in Mahawilachchiya (0.61), Kahatagasdigiliya (0.52), and Medirigirya (0.56) areas belong to the medium vulnerability class, and there is a statically significant variation among three farming communities ($P = 0.007$). Mainly, the selected three areas are highly vulnerable in terms of some sub-variables of built capital such as capital drinking water, irrigation facilities, and elephant fences. There is no significant variation in vulnerability among the three farming communities in terms of financial capital ($P = 0.276$). However, capital index values vary as 0.36, 0.33, and 0.35 for Mahawilachchiya, Kahatagsdigiliya, and Medirigiriya areas, respectively. Sub variables of financial capital show that three farming communities are highly vulnerable in terms of family income saved money, crop insurance, life insurance, and off-farm income, except for adequate land and available functioning bank accounts.

According to spiritual capital, all three areas belong to medium vulnerability, and there is a significant variation in vulnerability among the three farming communities in Mahawilachchiya, Kahatagasdigilya, and Medirigiriya ($P = 0.001$). Sub variables

Table 3 Summary of the nine capitals of CCF for three selected areas in NCP

Capital	Mahawillachchiya	Vulnerability class	Kahatagasdigiliya	Vulnerability class	Medirigiriya	Vulnerability class
Human	0.21	Very high	0.19	Very high	0.18	Very high
Cultural	0.38	High	0.39	High	0.41	High
Social	0.60	Medium	0.53	Medium	0.60	Medium
Political	0.10	Very high	0.11	Very high	0.08	Very high
Natural	0.33	High	0.33	High	0.39	High
Built	0.61	Medium	0.52	Medium	0.56	Medium
Financial	0.36	High	0.33	High	0.35	High
Spiritual	0.67	Medium	0.58	Medium	0.74	Medium
Technological	0.38	High	0.37	High	0.40	High

Table 4 Evaluating the significance of vulnerability changes in terms of nine capitals among Mahawillachhciya, Kahatagasdigiliya, and Medirigiriya in NCP

Capital	*P*-value	Hypothesis	Decision
Human	0.345	Not significant	There is no significant variation in vulnerability in terms of human capital
Cultural	0.540	Not significant	There is no significant variation in vulnerability in terms of cultural capital
Social	0.020	Significant	There is a significant variation in vulnerability in terms of social capital
Political	0.920	Not significant	There is no significant variation in vulnerability in terms of political capital
Natural	0.044	Significant	There is a significant variation in vulnerability in terms of natural capital
Built	0.007	Significant	There is a significant variation in vulnerability in terms of built capital
Financial	0.276	Not significant	There is no significant variation in vulnerability in terms of financial capital
Spiritual	0.001	Significant	There is a significant variation in vulnerability in terms of spiritual capital
Technological	0.774	Not significant	There is no significant variation in vulnerability in terms of technological capital
Kruskal-Wallis test Monte Carlo significant *P*-value: 0.05			

of spiritual capital show that all three farming communities are very high and vulnerable in terms of spiritual maturity to bear the losses. All three studied areas are corrected with high vulnerability in terms of technological capital, and there is no statistically significant variation among the three farming communities in Mahawilachchiya, Kahatagsdigliya, and Medirigiriya ($P = 0.774$).

Figure 3 shows how nine capitals of CCF change according to the ranking done based on capital index value. When considering the whole study area or NCP, political, human, and financial capitals have been ranked first, second, and third, respectively. It means communities living in this area are most vulnerable in terms of political, human, and financial capital, and these same results are correlated with the Medirigiriya area related to political, human, and financial. The farming communities living in the Mahawilachchiya and Kahatagasdigiliya areas are most vulnerable in terms of political, human, and natural capital. However, farming communities in NCP are more highly vulnerable to drought in terms of political and human capital than other capitals.

4 Discussion

No research has been carried out in Sri Lanka to assess the vulnerability of drought using the Community Capital Framework (CCF) concerning farming communities at the micro level. Therefore, it is unable to compare the results of this study with those of previous researchers. However, CCF explains that the vulnerability of the

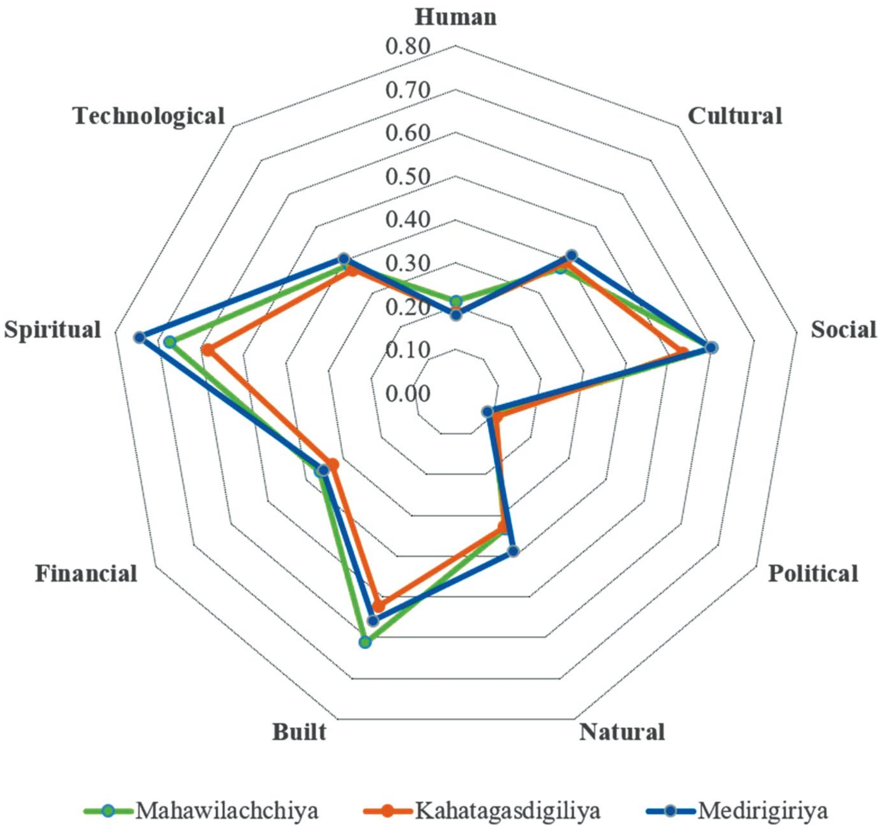

Fig. 2 Comparison of nine capitals of CCF related to three selected areas

farming communities in NCP is high (0.40). When comparing farming communities in three selected DSDs, i.e., Mahawilachchiya (0.41), Kahatagasdigiliya (0.37), and Medirigiriya (0.41) belong to the high vulnerability category, but Kahatagasdigiliya is the most vulnerable area than Mahawilachchiya and Medirigiriya. There is no significant variation in vulnerability among the farming communities in Mahawilachchiya, Kahatagasdigiliya, and Medirigiriya related to human, cultural, political, financial, and technological capital, and there is a significant variation in vulnerability among the three farming communities in terms of social, natural, built, and spiritual capitals. The most exciting finding is that political capital and human capital have become first and second in terms of community vulnerability to drought out of nine capitals in all selected areas. After Covid 19, Sri Lanka has undergone an economic crisis. Hence, Sri Lanka society is passing a difficult period due to government policies such as the high cost of seeds, manure, agrochemicals, living costs, reducing subsidies, imposing the unbearable tax, not creating a healthy market for farmers' crop production, not paying enough compensations for harvest loss due to drought, not introducing proactive drought risk management system, not

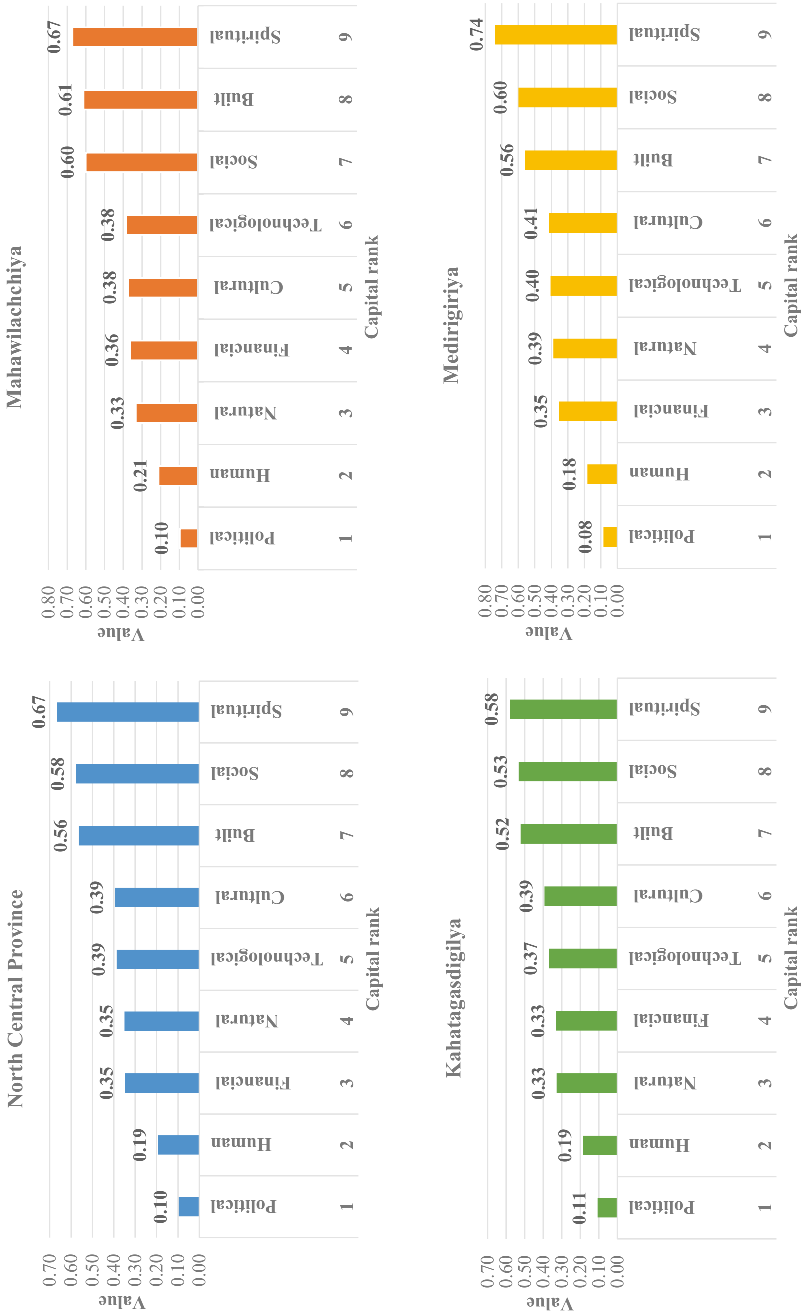

Fig. 3 Ranking nine capitals according to capital index value

rehabilitation of tank cascade systems in NCP, etc. Hence, a considerable gap has been created between the government and farming communities concerning their relationship and trustworthiness. It was observed that farmers are refusing politicians, so these reasons may be affected by political vulnerability in the area. When exploring why human capital is secondly most vulnerable, it was observed that most of the farmers receive low income because of failure of agriculture due to various reasons such as frequent drought events, animal damage to the crops, particularly elephants, peacocks, and monkeys, high cost of agricultural inputs, not the suitable market price for the farmer's crop production, etc. On the other hand, the educational levels of the farmers are lower than those of other parties, so it is hard for them to find government or private jobs. Hence, farming communities solely depend on agriculture as their major livelihood. Farmers have limited access to off-farm income. When considering the health condition of the farming community in the NCP, they have undergone various diseases such as cancer, chronic kidney disease of unknown (CKDu), etc. In particular, previous research findings have revealed that around 10–12% of the farmers in the NCP have undergone CKDu. These reasons may increase the human vulnerability among farming communities in the NCP. None of the nine capitals of CCF belong to low vulnerability. Spiritual and Social capital belongs to the medium vulnerability because capital index values range from 0.53 to 0.74. It was observed that there is a good relationship between the farming community in the NCP and religious institutions, and they are engaged in religious activities according to their own religious beliefs. Sometimes, farming communities have been practicing some specific rituals from ancient times to avoid difficulties created by natural hazards. For example, when facing drought events, Buddhist farmers get chanted by Buddhist monks some specific *Pirith* sermons (*Wesi piritha*) preached by the Lord Buddha and hope to receive rain. These kinds of activities may help to reduce the vulnerability in terms of spiritual capital, and these customs may help build the mental strength of the farmers.

5 Conclusions

Community Capital Framework (CCF) is one of the best tools to assess the social vulnerability related to drought hazards because it provides multiple dimensions to analyze social vulnerability. On the other hand, it is easy to understand the capital of CCF, and results can be effectively used for decision-making, policy-making, and planning strategies to reduce the vulnerability and build the resilience of the farming community. The farming community in the NCP ranges from very high to medium vulnerability-related drought. There is a significant variation in vulnerability among the farming communities in terms of social, natural, built, and spiritual capital. At the same time, there is no significant variation in vulnerability among the community related to human, cultural, political, financial, and technological capital. The farming communities in the NCP are very high in terms of political and human capital. The farming communities belong to medium vulnerability in terms of social, spiritual, and built capital. At the same time, farmers in NCP are highly vulnerable in terms of cultural, natural, financial, and technological capital. A proactive drought risk management system should be introduced to reduce social vulnerability, addressing the very high and highly vulnerable capitals of the CCF. These results will be helpful for policymakers.

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Quantifying Glacier Retreat and Elevated Lake Growth Using Remote Sensing for Disaster Management in the Western Himalayas

S. N. Remya, Varsha Prem, Sai Hari Chandana Ekkirala, and Sudha Arlikatti

1 Introduction

The state and fate of Himalayan glaciers have become primary concerns for the scientific community and policymakers. In the Himalayas, lake-terminating glaciers are retreating and thinning faster than land-terminating glaciers, leading to higher rates of glacier mass loss (Liu et al., 2020). The mass changes in glaciers are indicators of climate change, and these glacial fluctuations in recent decades have caused the formation and enlargement of glacial lakes in many parts of the Himalayas. As glaciers melt, they release water that collects in depressions in the landscape (Remya et al., 2019). These depressions can eventually fill up to form lakes. There are an estimated 5000 glacial lakes in the Himalayas (Veh et al., 2020; Zheng et al., 2021; Carrivick & Tweed, 2013), and they are expanding at a rapid rate (Nie et al., 2017; Zhang et al., 2015; Wang et al., 2020). The expansion of glacial lakes in the Himalayan region is a serious problem that is likely to worsen in the future as climate change continues. In the future, such glacial lakes can create Glacial Lake Outburst Flood (GLOF), which can cause extensive damage to the natural environment, human property, life, and livelihoods (Huggel et al., 2004). The tragedy that occurred in the Himalayas during 2013 was the outburst of Chakrabarti Lake in Uttarakhand Himalayas, which caused the loss of 8000 people and lots of human distress and infrastructure (Bhattacharyya et al., 2017). Satellite remote sensing has proved to be the best technique for monitoring glaciers and glacial lakes in the Himalayas, as they are situated at high altitudes and in rugged climatic conditions. Thus, keeping in view, we have identified one proglacial lake associated with a

S. N. Remya (✉) · V. Prem · S. H. C. Ekkirala · S. Arlikatti
Amrita School for Sustainable Futures, Amrita Vishwa Vidyapeetham, Amritapuri Campus, Kollam, Kerala, India
e-mail: remyasn@am.amrita.edu; sudhaarlikatti@am.amrita.edu

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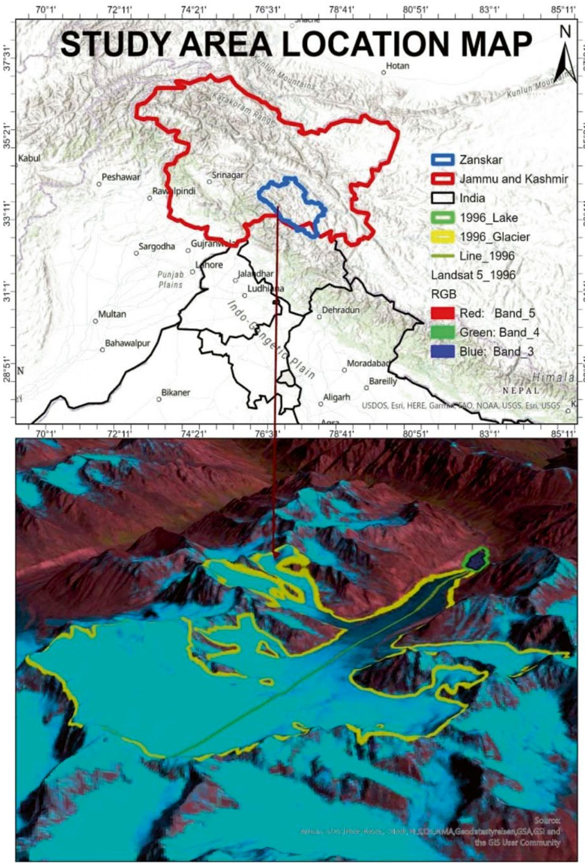
glacier within the Western Himalayas. Our objectives are to get the aerial expansion of the lake and the area of glaciers that evacuated from the historical period to the recent period. Besides, we calculated the lateral retreat of glaciers from 1996 to 2022. The preliminary data source used is the freely available Landsat series from 1996 to 2022. The study provides insight into monitoring glacial lakes in the Himalayas where satellite data are the preliminary source. The state and fate of Himalayan glaciers have become primary concerns for the scientific community and policy-makers.

2 Study Area

The current study region (26 km^2) is a portion of the Western Himalayan Indus Basin's Zanskar subbasin. Numerous glacial records can be found in the Zanskar Basin, which is located between the Greater Himalayan range and the Ladakh mountain range (Mitchell et al., 1999). The Zanskar mountain range experiences snow accumulation on glaciers because of the South Asian summer monsoon, which mostly forms valley glaciers and tongue glaciers. Numerous well-known glaciers are in the Zanskar subbasin, and the names of these glaciers are noted and adapted from the Survey of India Topographic Maps by Mir et al. (2018). The Padam glacier is named after its proximity to Padam town, a significant administrative tehsil in the Kargil area of Jammu and Kashmir, India. The glacier runs north-easterly in the Zanskar region and merges with the Stod River in Padam town. In other words, the Padam Glacier is named after the town it is near, and it flows into the town (Mir et al., 2018).

The snow/mass accumulation processes of these glaciers include avalanches, blowing snow, and direct snow (Mir et al., 2018). Because of western disturbances and summertime rains, the region receives most of its snowfall throughout the winter season (Mir et al., 2018). The weather at the Leh station, which is adjacent to the Zanskar Basin, recorded mean annual precipitation of about 93 mm, compared with the Zanskar region's stated mean annual precipitation of about 250 mm (Klimes, 2003). From the southeast to the northwest of the region, the pattern of precipitation shifts. At Padam Glacier, snowfall varies between 2.05 and 6.84 mm (Raina & Koul, 2011). At lower elevations, this region's precipitation occasionally manifests as rain. Leh stations' mean annual maximum and minimum temperatures range from 23.7 °C in August to −15.6 °C in January (Singh, 1998). The location of the study area is depicted in the image below (Fig. 1).

Fig. 1 Study area map



3 Data and Methods

Satellite images from 1996 to 2022 were utilized to get the outlines of glaciers and lakes for the study. The details of the images are presented in Table 1. Satellite images are the best tool for obtaining historical landscapes in high mountainous terrain (Remya et al., 2019). We used satellite images from 1996 to 2022 from the United States Geological Survey (USGS) for the Landsat images to get the glacier and lake extents. Manual digitization was carried out to get the glacier and lake outlines in each image using ArcGIS pro-environment. The glacier length was calculated each year, with a line drawn from the highest elevation point of the glacier to the terminus. Furthermore, the glacier area and the lake area along with the glacier retreat were calculated from 1996 to 2022. The detailed methodology flow chart is given below (Fig. 2).

Table 1 Details of the satellite data used

S. no.	Satellite data	Year	Date	Source	Purpose
1	Landsat 5	1996	01-09-1996	USGS—Earth Explorer	For glacier/lake boundary
2	Landsat 5	2001	06-07-2001	USGS—Earth Explorer	For glacier/lake boundary
3	Landsat 5	2010	17-09-2010	USGS—Earth Explorer	For glacier/lake boundary
4	Landsat 8	2016	10-10-2016	USGS—Earth Explorer	For glacier/lake boundary
5	Landsat 9	2022	03-10-2022	USGS—Earth Explorer	For glacier/lake boundary

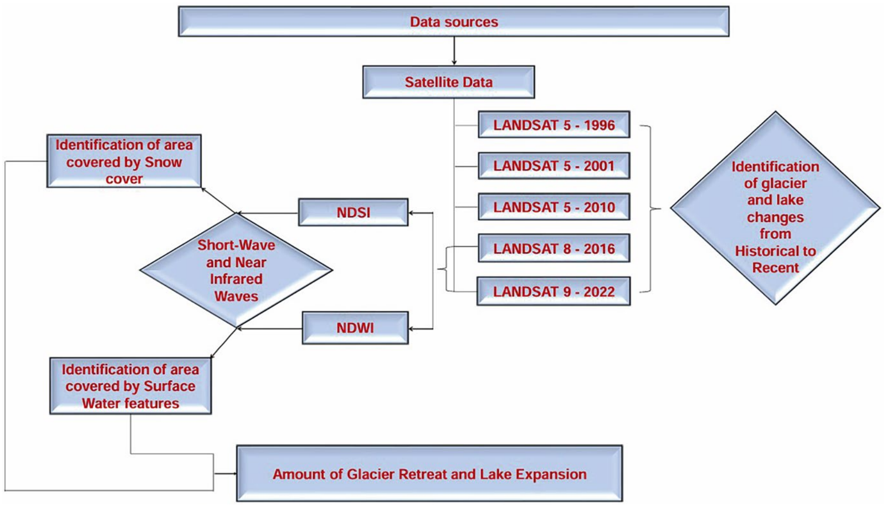


Fig. 2 Methodology flow chart

4 Results and Discussion

The present study provides information about glacier area reduction and lake expansion in the Zanskar region of the Western Himalayas in 1996, 2001, 2010, 2016, and 2022. The 1996, 2001, 2010, 2016, and 2022 data clearly show glaciers and lakes in the band combination of 5, 4, and 3. The glaciers and lakes of the year are shown in Fig. 3.

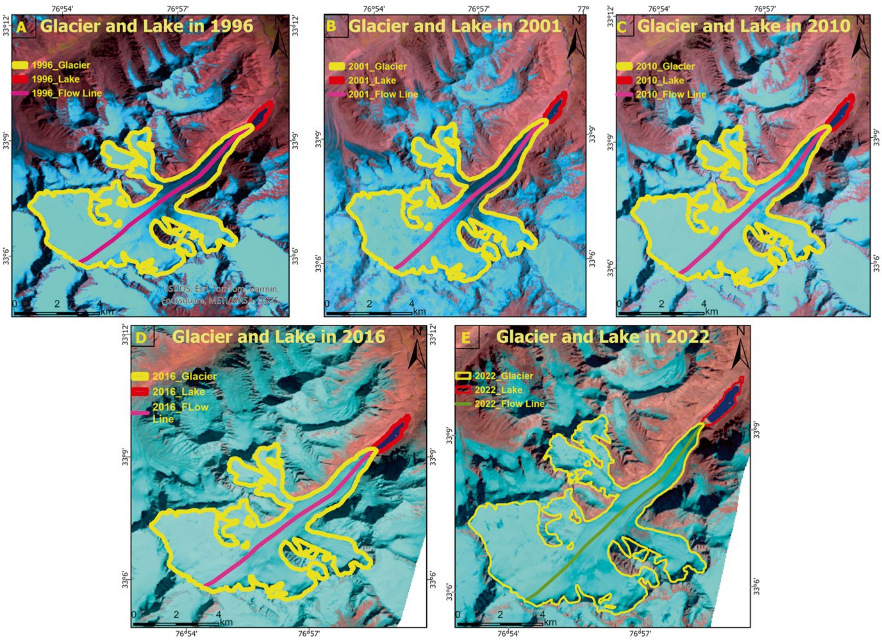


Fig. 3 Glacier and lake changes from 1996 to 2022: (**a**) glacier and lake in 1996; (**b**) glacier and lake in 2001; (**c**) glacier and lake in 2010; (**d**) glacier and lake in 2016; (**e**) glacier and lake in 2022

For each year, the glacier starts retreating, and the lake starts expanding. The study area glacier shows a 1.9% decrease and the lake shows a 45.6% increase during the years 1996–2022. The changes are shown in Figs. 4 and 5. Tables 2 and 3 show the areas of the glacier and lake, respectively.

Over the course of 26 years, there has been a noticeable reduction in the glacier area and an increase in the lake area. There was a reduction of 0.34 km^2 in the glaciated area and an increase of 0.30 km^2 in the lake area, indicating a faster rate of ice melt over the years, as illustrated in Fig. 6. This calls for further examination of the climatic conditions of the region and potential anthropogenic consequences due to the increase in water content within the region. Potential consequences could be increased chances of flooding due to rising water levels and landslides due to infiltration. One method for understanding this is to conduct water budget modelling and validation for the region, considering the elements at risk present around the glacier. The results obtained from the above methods are compared using spectral indices, as discussed in Sect. 4.1.

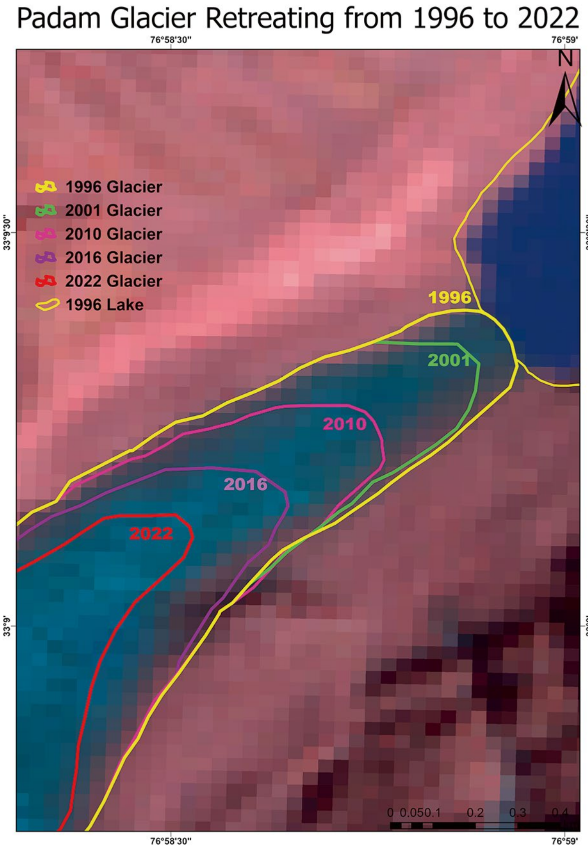


Fig. 4 Glacier retreating from 1996 to 2022

4.1 Comparison Study

Spectral indices such as the Normalized Difference Snow Index (NDSI) and the Normalized Difference Water Index (NDWI) are used to monitor changes in glaciated areas and abutting lake areas (Debnath et al., 2018). This is explicitly done for the years 2016 and 2022 using Landsat 8 and Landsat 9 images because of the availability of the shortwave infrared and near-infrared bands required for calculating the spectral indices (Debnath et al., 2018). A further comparative study was done by verifying the area of the glacier obtained from the satellite images and the snow cover area obtained through the NDSI. Similarly, the area of the lake from the satellite images was compared with the area of the water bodies using the spectral index of the NDWI. The degree of change in the area obtained from both methods is presented below.

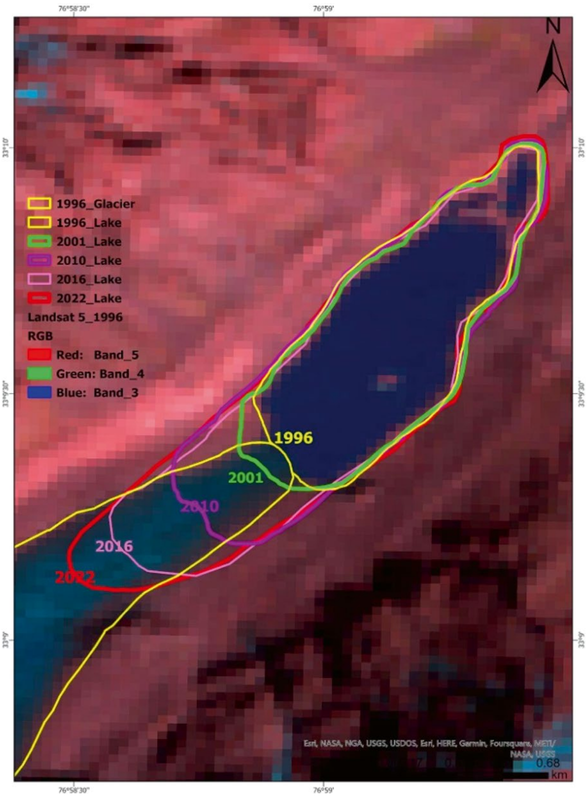


Fig. 5 Glacial lake expansion from 1996 to 2022

Table 2 Glacier retreat from 1996 to 2022

S. no.	Year	Area (km^2)	Length (m)
1	1996	26	9.74
2	2001	25.93	9.64
3	2010	25.85	9.40
4	2016	25.73	9.14
5	2022	25.50	9.01

Table 3 Lake expansion from 1996 to 2022

S. no.	Year	Area (ha)
1	1996	52.00
2	2001	54.04
3	2010	68.59
4	2016	72.15
5	2022	82.71

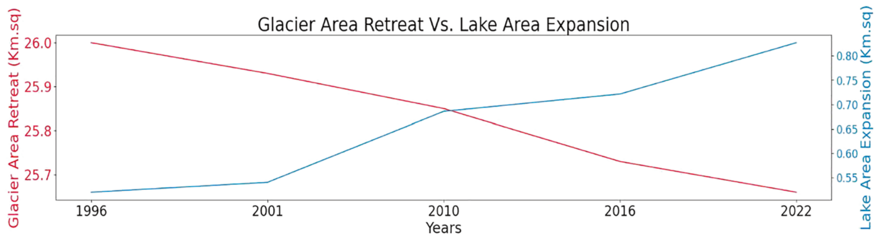


Fig. 6 Glacier area retreat vs. lake area expansion (km^2)

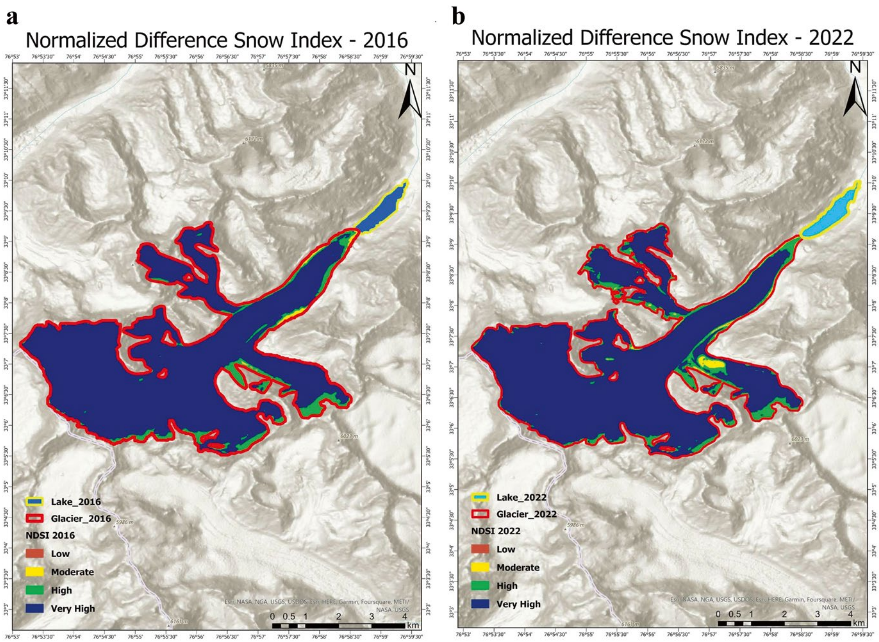


Fig. 7 (**a**) NDSI—2016. (**b**) NDSI—2022

4.2 Normalized Difference Snow Index

Normalized Difference Snow Index (NDSI) is a useful tool for separating the spectral signatures of snow from those of vegetation, soil, and lithology. The NDSI of the study area is shown in Fig. 7a, b. It utilizes the green and shortwave infrared bands to identify ice and snow pixels. The pixel threshold index of + ≥0.4 differentiates as ice and snow-covered areas (Debnath et al., 2018). SWIR is particularly useful for measuring water content because water absorbs the SWIR wavelength. This can usually be done through bands 3 and 6 of the Operational Land Imager Satellites (Landsat 8 and 9) from the USGS, 2023.

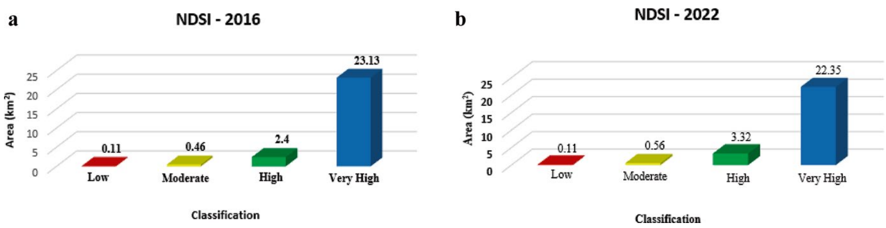


Fig. 8 (**a**) NDSI—2016. (**b**) NDSI—2022

Table 4 Changes in glaciated area using Landsat image and derived NDSI for 2016 and 2022

Year	Landsat image (area in km^2)	NDSI (area in km^2)
2016	25.73	25.81
2022	25.50	25.94

$$\text{NDSI} = \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}} \tag{1}$$

Figure 8a, b represents low, moderate, high, and very high regions of snow-covered areas in 2016 and 2022. Figure 8a shows the area of the NDSI in 2016. In 2016, the very high snow cover area was estimated to be 23.13 km^2 and the lowest snow cover area was 0.11 km^2. Figure 8b represents the area of snow cover in 2022. In 2022, the very high snow cover area was estimated as 22.35 km^2 and the lowest snow cover area was 0.11 km^2.

Two measurements are derived from this, the difference in the Landsat image areas with respect to the NDSI image for each year and the change in snow-covered areas from 2016 to 2022. It has been noted that for 2016, the Landsat image indicated a glaciated area of about 25.73 km^2 and the NDSI indicated a glaciated area of 25.81 km^2, indicating that the difference in area was about 0.08 km^2. However, for the year 2022, the Landsat image showed a glaciated area of 25.50 km^2 and the NDSI showed a glaciated area of 25.94 km^2, indicating a difference of 0.13 km^2**.**

The same is depicted in Table 4. Additionally, the NDSI images from 2016 to 2022 indicate a decrease in the glaciated area by about 0.13 km^2. However, the Landsat images indicate a reduction in the glaciated area by 0.23 km^2, showing an uncertainty of about 0.10 km^2 between the two methods.

4.3 Normalized Difference Water Index

The Normalized Difference Water Index (NDWI) is a good indicator for identifying surface water features in satellite images and monitoring changes in the water content of water bodies. It is also capable of measuring the moisture content in soil (Debnath et al., 2018). The NDWI of the study area is shown in Fig. 9a, b. It utilizes the NIR and SWIR bands, which are capable of differentiating between

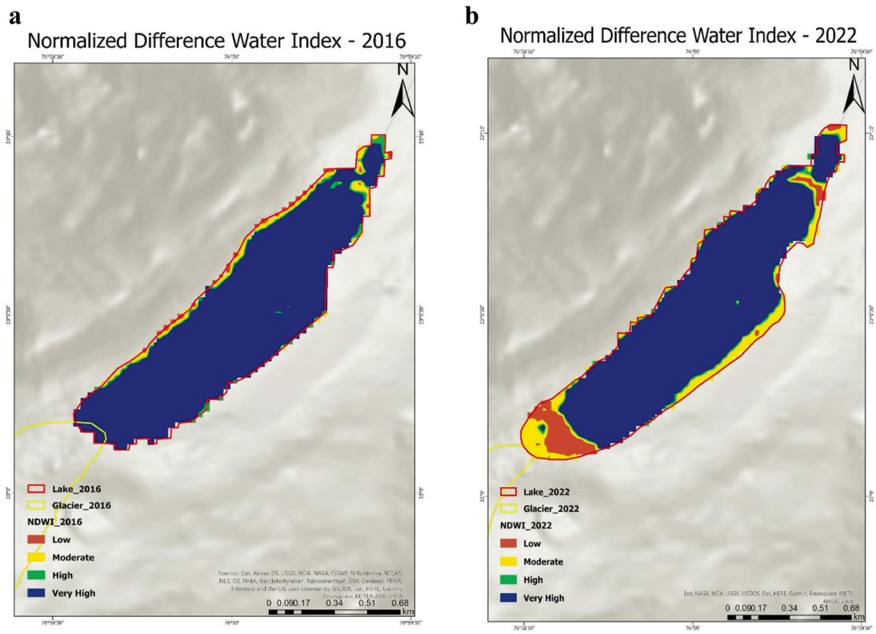


Fig. 9 (**a**) NDWI—2016. (**b**) NDWI—2022

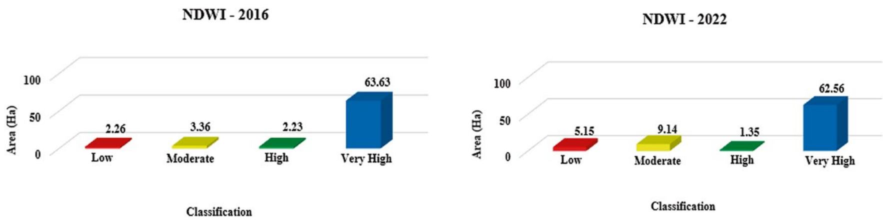


Fig. 10 (**a**) NDWI—2016. (**b**) NDWI—2022

the spectral signatures of vegetation and water to detect small changes in water content.

$$\text{NDWI} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}} \tag{2}$$

Figure 10a, b shows the graphical representation of low, moderate, high, and very high water covered areas in 2016 and 2022. The very high region covers 63.63 and 62.56 ha of area in 2016 and 2022, respectively. The lowest portion of the area was covered by 2.26 ha in 2016 and 5.15 ha in 2022.

Like the use of the NDSI, two measurements were derived from the NDWI. The uncertainty in the increase in the lake area calculated from the satellite image and the area of increase in the lake calculated through the NDWI image are presented for both years. In 2016, the area of the lake was calculated to be 72.15 ha and the area of increase of the lake was calculated to be 70.50 ha through the NDWI image, indicating a difference of 1.65 ha. Similarly, for the year 2022, the Landsat image

Table 5 Changes in lake area using Landsat image and derived NDWI for 2016 and 2022

Year	Landsat image (area in ha)	NDWI (area in ha)
2016	72.15	70.50
2022	82.71	76.04

indicated that the lake area was 82.71 ha and the NDWI image indicated a lake area of 76.04 ha, showing a difference of 6.67 ha between the two images. Additionally, the NDWI images from 2016 and 2022 indicated an increase in lake area of 5.54 ha. However, the Landsat images from 2016 and 2022 indicated an increase in lake area of 10.56. This informs an uncertainty of about 5 ha between the two methods used, which is a minor difference. Both methods strongly indicate a decrease in the glaciated area and an increase in the abutted lake area, confirming the hypothesis presented (Table 5).

5 Conclusion

Our study highlights a significant and concerning trend in the Himalayan region, where glacial lakes are expanding at an alarming rate, growing by 45.6% more than in recent decades compared with historical times. This study serves as a valuable example of the profound consequences of glacier retreat in the region. There are many studies available in the Eastern and Western Himalayas on the glacial lake expansions (Bhutiyani et al., 2008; Kumar et al., 2020; Zhang & Liu, 2019; Shrestha & Aryal, 2011). These studies are all regional-based studies. While numerous regional-based studies have been conducted in the Eastern and Western Himalayas, there remains a pressing need for comprehensive research spanning across high mountain Asia (HMA). Specifically, we intend to investigate glacier thinning rates and their integration with lake volume, providing critical insights into the extent to which glacial ice contributes to the expansion of these lakes. These endeavours carry substantial implications for the sustainability and well-being of communities downstream in the Himalayan region.

This study not only is pertinent to the scientific community but also holds immense significance for policymakers and disaster management authorities. By comprehending the evolving patterns of ecological change and assessing the risks of flash flooding and associated landslides, we also propose early warning systems to safeguard remote mountain communities. Furthermore, our findings can inform effective water resource management strategies for downstream communities and contribute to adaptive measures against the challenges posed by climate change in high mountain regions. Our work highlights the urgent need for continued research and collaboration to address the complex relationship between glacier retreat, glacial lake expansion, and the well-being of Himalayan communities. By doing so, we can build a more resilient and sustainable future for this ecologically vital region.

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Exploring the Role of Physiotherapists in Disaster Management

Maman Paul

1 Introduction

Human survival is continuously facing risks in many ways including both human-made and natural disasters. Disasters are sudden events that saturate the existing resources of the local area and require outside help from national and international organizations (Harrison, 2007). Disasters are sudden and catastrophic events that badly disrupt the performance of the affected area (Trivedi & Rathod, 2017). Natural disasters occur in the form of uncontrollable floods, horrifying hurricanes, tornadoes, sudden volcanic eruptions, and devastating earthquakes (Bankoff et al., 2004). A striking increase in the incidence and severity of high-intensity sudden-onset natural disasters was observed in the last century. Worldwide, innumerable people are affected by disasters, especially vulnerable are the people from low- and middle-income countries, who are inexplicably impacted (Hodgson, 2021).

The Center for Research on the Epidemiology of Disasters defines disasters as happenings that ravage native resources and need outside help. Disaster hit regions if poorly resourced, people were not able to execute disaster response plans, including physical rehabilitation or helping people with new or preexisting disabilities (Trivedi & Rathod, 2017). The International Federation of Red Cross and Red Crescent Society defines a disaster as an unexpected devastating happening that significantly disrupts the functioning of the affected area, causing both human and material losses, as well as financial and environmental damages that surpass the area's capacity to recover using its own resources (International Federation of Red Cross and Red Crescent Society, 2022). Both forms of disasters were common, i.e., natural and human-made disasters. In India, during the 2001 earthquake in Kutch, numerous people suffered from variable disabilities. Prominent examples of significant catastrophes in the last 15 years include the earthquake that occurred in Haiti

M. Paul (✉)
Department of Physiotherapy, Guru Nanak Dev University, Amritsar, Punjab, India

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in 2010 and the Tohoku earthquake and subsequent tsunami in Japan in 2011, which also resulted in the Fukushima Daiichi nuclear disaster, Typhoon Haiyan in the Philippines in 2013, and the earthquake in Nepal in 2015. These catastrophes were associated with the loss of immeasurable lives and shelterless people. The communication of hazards related to disasters with already existing poor sociopolitical circumstances, encompassing health disparities, poverty, and inadequate urban planning, among other factors, leads to further distress (United Nations, 2017).

On February 2, 2024, dangerous fires suddenly ignited at four spots in Chile's Valparaíso region, leading to considerable damage This event was one of the most lethal forest fires in Chile's history and the most overwhelming disaster in the country since the earthquake and tsunami that hit the country in 2010 that has killed more than 500 people and led to $30 billion loss (Center for Disaster Philanthropy, 2024).

Disasters are accompanied by the loss of innumerable lives, property, etc., and these events often lead to loss of life and property damage, with subsequent economic repercussions. The severity of these impacts varies based on the resilience and recovery capacity of the affected population, interruption in basic services, and the available infrastructure (Bankoff et al., 2004). Disasters can stem from natural phenomena such as geophysical, meteorological, hydrological, climatological, and biological events, as well as from human activities, and are thus classified as human-made (CRED). Human-made disasters may take place in the form of technological or ecological disasters due to certain actions of humans, which may be conscious or as such (Joshua et al., 2014).

Natural disasters lead to morbidity, mortality, and long-term disability, as well as affect individuals, community, and society (Kerridge et al., 2012). Disasters pose substantial challenges for vulnerable populations, often resulting in a multitude of physical disabilities such as spinal cord injuries, severe head injuries, amputations, fractures of bones, and damage to the peripheral nerves (Navjyot & Priyanshu, 2017; Noji, 1997; Rando, 2005). The standard emergency medical response considers physical survival as its top priority, and all resources are mobilized to save as many lives as possible. Furthermore, emergency medical response gives priority to cure than care and independence (Van Damme et al., 2002).

During disasters, healthcare providers and participants involved in different ways use their institutional and leadership expertise to assist disaster-hit victims with logistic and administrative needs besides dealing with emotionally traumatized people. Professionals should be involved in disaster response at an early stage to reduce the number of deaths and physical disabilities and to enhance the medical recovery of disaster survivors (Waldrop, 2002).

The management of disasters comprises the following phases: prevention, preparation, planning, immediate response, and recovery. A multidisciplinary approach with medical and nonmedical interventions is required to work for these stages. Medical interventions should emphasize the crucial role played by physiotherapists as members of an interdisciplinary healthcare team in various aspects of patient care, particularly in disaster management scenarios (WCPT, 2016).

2 Present Scenario

The literature indicates that the major barrier to endorsing the involvement of physiotherapists in disaster management has historically faced challenges due to reluctance from both physiotherapists and bodies dealing with disaster response. Another reported barrier was the absence of formal recognition of the role and contribution of physiotherapists as well as insufficient understanding of their capabilities among both physiotherapy professionals and those coordinating relief efforts in disaster management. According to Article 11 of the United Nations Convention on the Rights of Persons with Disabilities (United Nations, 2006), during disasters and conflicts, it is mandatory for nations to offer assistance to people with disabilities. The significance of rehabilitation mediation in the initial phases of disaster response, as well as in the community setting during the months and years that follow a disaster, is highlighted. The evidence supports that rehabilitation plays a crucial part in enhancing the standard of living and well-being of individuals with permanent disabilities resulting from disasters. By integrating rehabilitation professionals into emergency response teams, one can accomplish improved medical results in the healing of wounds and support self-sufficiency in physical abilities among affected individuals (Tataryn & Blanchet, 2012). The major problem with rehabilitation services was the right time and place of delivery (Gosney et al., 2011). On the other hand, statistics revealed a decrease in the mortality rate from disasters compared with the number of individuals who survived but sustain injuries (Ritchie et al., 2022).

Disaster preparedness encompasses three key stages: prevention, medical treatment, and rehabilitation (Kalra et al., 1993; Khan et al., 2003). Rehabilitation is crucial in disaster response and is defined as a collection of actions aimed at helping individuals who have or are at a risk of disability, attain and sustain their highest level of functioning in relationship with their surroundings. Timely rehabilitation interventions can lead to better health results, lower hospital admissions, and a reduction in extended-term incapacitation. The goal of rehabilitation is to enhance a person's capacity for performing work and positively influence the milieu (National Health Services Clinical Advisory Groups Report, 2010; World Health Organization, 2011).

3 Role of Physiotherapists

Rehabilitation plays an important role in crisis handling and restoration efforts. It entails helping individuals impacted by disasters in bringing back their physical, psychological, and social capabilities, with the goal of lessening long-term effects such as physical disabilities, health issues, and mental health challenges. By improving quality of life and facilitating early recovery, rehabilitation also supports the successful reintegration of disaster victims into their communities (Amatya & Khan, 2023). Individuals who received rehabilitation from a multidisciplinary team consisting of physical therapists (PTs), occupational therapists (OTs), a recovery nurse, and psychological counselor demonstrated greater improvement in extended physical performance as compared with individuals who only received rehabilitation, as evidenced 1 year after the incident (Zhang et al., 2013).

Physiotherapists' participation in disaster response is warranted because of their capacity to address a variety of injuries commonly seen in such scenarios, such as respiratory issues, burns, life-threatening conditions, and musculoskeletal trauma. Participants in disaster response efforts typically engage in two main areas: (1) patient care and (2) the administration of rehabilitation services, including physiotherapy services. Patients can be categorized into two primary groups: rescue workers, who may sustain slight musculoskeletal injuries and respiratory issues, and individuals who are directly wounded in a disaster. The medical health conditions observed among these individuals encompass a wide range, including musculoskeletal trauma, lesions, compression injuries, ballistic injuries, high-velocity penetrating wounds, internal bleeding, and critically ill victims. Areas where participants believed their abilities could have been more effectively employed include wound care, triage, managing musculoskeletal trauma, and administering initial medical assistance. This underscores the potential for physiotherapists to contribute significantly to disaster response efforts by addressing a variety of medical needs among affected individuals and rescue workers alike. The anticipatory part physiotherapists could play need to be emphasized, and their involvement may play a role in preventing musculoskeletal injuries and respiratory problems among rescue workers. Physiotherapists involved in emergency relief work undertake various roles, encompassing musculoskeletal care, neuromuscular interventions, management of injuries including burns, and cardiorespiratory care, among others. By assuming certain responsibilities traditionally handled by physicians, such as triage and less severe case management, physiotherapists help ensure that physicians are available to address more critical cases, optimizing overall patient care during disaster response efforts (Harrison, 2007).

Grissom and Farmer (2005) substantially supported the notion that physiotherapists possess unique skills that are valuable in disaster response efforts. Despite their participation in such endeavors with some success, their roles have often been poorly defined, thus restraining their efficiency. Physiotherapists have valuable skills for disaster response, including the ability to assess and manage fatalities with severe injuries, protect emergency personnel from sustaining injuries, and mitigate the development of chronic dysfunction among patients in the aftermath of the emergency phase. Moreover, physiotherapists have the potential to share the responsibilities of medical personnel, thus contributing to a more functional and holistic perspective on disaster response efforts (Center for Research on the Epidemiology of Disasters, 2006).

The World Confederation of Physical Therapy (WCPT) stated that the responsibilities of physiotherapists in emergency situations were developing, driven by their expertise in disability management and functioning. The knowledge they possess makes them well suited to offer support for humanitarian relief efforts, especially in regard to assisting in the recovery of injured individuals impacted by natural disasters. Considering the potential impact of disasters and the associated debilitating limitations, it is becoming more evident that physiotherapists will play an increasingly integrated role in future emergency response teams (WCPT, 2016). However, in 2002, Waldrop observed that even though physiotherapists in the USA were participating in disaster management, their responsibilities were not well defined.

4 Discussion

In 2004, a document was released in the United States that explained the responsibilities of physiotherapists during disaster response. This was followed by a broader global report by the World Confederation of Physical Therapy (WCPT) in 2016, which was more extensive. According to the WCPT report, physiotherapists have several functions during the immediate response stage of a disaster, including evaluating the overall requirements for rehabilitation in the disaster-stricken region; identifying existing rehabilitation and other specialized services for individuals with trauma; and furnishing immediate rehabilitation services in nearby medical facilities, communities, and nongovernmental organizations. In the rehabilitation phase of disaster management, physiotherapists' responsibilities include ensuring the continuity of care for individuals with ongoing rehabilitation needs, advocating for inclusive reconstruction efforts that consider the needs of individuals with disabilities, and strengthening the ability of community services to address both present and potential disasters (Harrison, 2007).

Trivedi and Rathod (2017) explored the function of physiotherapists involved in disaster management during the 2004 tsunami in South India and in Western India during the 2001 earthquake. Research has shown that physiotherapists are not involved in the initial phase but play important roles in wound management, assessing physical impairments and challenges, and administering treatment during the reaction and restoration phases of disaster management. Research indicates that starting rehabilitation within 90 days after an earthquake leads to better clinical results than beginning rehabilitation more than 90 days after the event (Li et al., 2012). Mulligan et al. (2015) found that physical therapists who were involved in the Canterbury earthquake in February 2011 not only provided physical care but also offered psychological support to survivors. Similarly, Nepal's Physiotherapy Association (2015) outlined the physiotherapists' contributions during earthquakes that hit Nepal in 2015, stating their essential involvement in patient assessment, transfer, and acute injury management.

The present review delves comprehensively into the factors influencing the role of physiotherapists in disaster management from the beginning till end of rehabilitation. The multifaceted dynamics of the involvement of physical therapists comprise of four main themes, i.e., individual and societal dynamics, administrative assistance, professional factors, and preparedness deliberations. The present review throws light on the pivotal role played by physiotherapists in the milieu of physical recuperation in disaster management (Tan, 2024).

5 Challenges in Disaster Management

There are numerous challenges for thriving and efficient rehabilitation postdisaster and skillful management of central organizations at the international and national levels, readiness and assurance of countries for preparedness, development of local rehabilitation competence in the form of investment in the education and skill enhancement of healthcare practitioners, and robust infrastructure, together with healthcare facilities, emergency shelters, transportation networks, and communication systems, is crucial (Amatya & Khan, 2023). The major challenges include the well-organized organization of health sites, the presence of stout systems for patient tracking and referrals, resource scarcity, and deficient site management, which need to be handled for shaping the landscape of physiotherapist participation (Tan, 2024). Archer et al. (2011) considered medical volunteers who are not adequately trained and experienced, as their participation in disaster response efforts can significantly impact the healthcare provided to disaster-hit individuals.

6 Suggestions

Numerous suggestions were given by physiotherapists regarding their role in disaster management. The recommendations provided could be categorized into two major areas: necessity aimed at additional skill enhancement and requirements intended for attitudinal shifts. Medical emergency training should be deemed crucial, alongside the expansion of new roles for physiotherapists within disaster response efforts. The literature recommends the need for further training for physiotherapists to work in disaster management, and their experience must be shared. The major challenge faced by physiotherapists is the dearth of recognized administrative guidelines on the involvement of physical therapists in emergency management. The present review resonates with the fundamental recognition of the role of interdisciplinary teamwork, comprehensible role demarcation, and resource allotment as the key components globally tailored to improve overall disaster response (Tan, 2024).

7 Conclusion

Physiotherapists possess a substantial capacity to address the instantaneous physical rehabilitation necessities of individuals experiencing injuries caused by disasters. Physiotherapists can make structured and impactful assistance from the initial planning phases to the execution of relief services. By dynamically engaging in disaster relief efforts, physiotherapists can make valuable contributions to the overall well-being and recovery of individuals affected by disasters, enhancing their quality of life and functional outcomes. It is essential for government organizations to delineate the extent of physiotherapists' services. Overall, further research is critical to better understand the involvement of physical therapists in responding to disasters and to develop evidence-based practices and policy development in this important domain.

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Part III

Environmental Pollution and Air and Water Quality

Identification of Upwind Source Regions Responsible for Pollution Episodes Over New Delhi During Premonsoon and Postmonsoon Seasons

Bhartendra Kumar and Shuchita Srivastava

1 Introduction

The escalation in air pollution is a growing concern, with the potential to significantly elevate the risk of disease and pose a severe threat to human well-being. Moreover, epidemiological investigations have demonstrated that the majority of airborne pollutants possess the capacity to induce respiratory tract infections, precipitate the development of lung cancer, and potentially curtail the human lifespan (Kan et al., 2012). Ambient air concentrations in megacities still remain high largely due to the rapid economic growth and increasing urban density. Air pollution is a serious international issue since it affects millions of lives worldwide.

In India, the Indo-Gangetic Plain (IGP) is acknowledged as the nation's primary agricultural region, covering 13% of its landmass and providing around 50% of the total national food output. Concurrently with advancements in agricultural practices, there has been a notable upswing in the generation of crop residues. The integration of contemporary agricultural machinery, such as cone harvesters, has resulted in substantial accrual of crop residues within fields. Regrettably, the deficiency of sustainable management practices for crop residues frequently leads to their combustion in agricultural zones (Ravindra et al., 2019). Punjab and Haryana, identified as major agricultural states in the Gangetic basin of India, contribute significantly to the country's crop production. As reported by Ravindra et al. (2019), around 90% of the rice in Haryana is cultivated, with approximately 75% of the area being harvested using combine harvesters. The quantity of crop waste generated and subsequently incinerated from these crops exhibits notable variations across different regions (Lohan et al., 2018).

The incineration of crop residue markedly amplifies the concentrations of various air pollutants, encompassing CO_2, CO, NH_3, NOx, SOx, nonmethane

B. Kumar (✉) · S. Srivastava
Indian Institute of Remote Sensing (ISRO), Dehradun, India

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hydrocarbons (NMHC), volatile organic compounds (VOCs), and particulate matter (PM) (Mittal et al., 2009; Zhang et al., 2011). NOx represents a combination of two gases of notable toxicological significance, namely nitric oxide (NO) and nitrogen dioxide (NO_2). These gases play pivotal roles in the genesis of smog, acid rain, and tropospheric ozone (Lammel, 1995). Carbon monoxide (CO), an odorless and colorless gas, is generated through the partial oxidation of compounds containing carbon. It is a crucial pollutant and serves as an indirect greenhouse gas. Additionally, CO acts as a precursor to the formation of tropospheric ozone. At higher levels, it can adversely affect human health by binding to hemoglobin in the bloodstream, forming carboxyhaemoglobin and causing carbon monoxide toxicity(Byard, 2019).

Potential source contribution function (PSCF) analysis has been employed in various prior research endeavors to construct a conditional probability function. This function facilitates the identification of potential locations serving as sources of detected pollution at a specific site (Zeng & Hopke, 1989). Gao et al. (1996) delineate the PSCF function as the conditional probability indicating the likelihood that an air parcel, with a pollutant concentration exceeding a predefined criterion, reaches a receptor site after traversing a particular geographical area. The PSCF model combines chemical data at the receptor location along with corresponding back air trajectories to track the potential upwind source regions. The main objective of this study is to identify the primary source locations responsible for the high mixing ratios of NOx and CO over New Delhi.

2 Methods

2.1 Study Area

This study focuses on identifying the source region of pollutants over New Delhi, which is located under the union territory of Delhi. New Delhi, the capital of India, is in the northern part of the country, extending from 28°24′17″N, 76°50′24″E to 28°53′00″N, 77°20′37″E with a spatial coverage of about 1483 sq. km. Delhi has an extreme climate. Summer, which spans from April to June, brings scorching heat, with the average temperature ranging from 25–45 degrees Celsius. In contrast, winter, encompassing December and January, is characterized by cold weather, with temperature varying from 22 degrees Celsius to the lowest 5 degrees Celsius. The city experiences an average annual rainfall of 714 mm. In the present work, the source attribution analysis of air pollutants is performed during two seasons. The first season covered the months from March to May, also known as the premonsoon period. The second season encompassed from September to November and is referred to as the postmonsoon period (Roy et al., 2011; WEC's Energy, 2010) (Fig. 1).

2.2 Workflow

Backward air trajectories can provide important information on potential source regions responsible for high levels of air pollution at the receptor location. These trajectories are then utilized in analyzing source-receptor models, such as

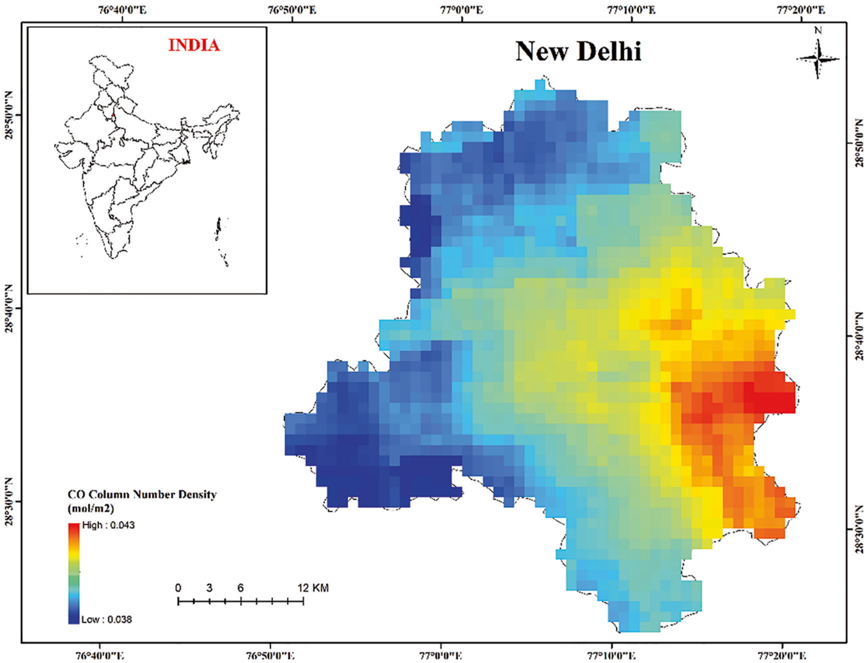

Fig. 1 Study area (New Delhi)

Quantitative Bias Trajectory Analysis (QTBA), Residence Time Analysis (RTA), Potential Source Contribution Function (PSCF), Areas of Influence Analysis (AIA) and Residence Time Weighted Concentrations (RTWC) (Hopke, 2016). In this study, the PSCF and CWT models are employed to examine the source regions responsible for high levels of carbon monoxide (CO) and nitrogen oxides (NOx) in the Delhi region.

2.3 HYSPLIT Model

The seven-day backward trajectories over Delhi (28.7041° N, 77.1025° E) were generated daily during 2018 for the premonsoon and postmonsoon periods using the HYSPLIT 4 (Hybrid Single Particle Lagrangian Integrated Trajectory) model. A starting height of 500 m AGL (above ground level) was used.

2.4 Meteorological Data

Three-hourly meteorological data are downloaded as a 1˚X 1˚GDAS file (Global Data Assimilation Studies) in ARL (Air Resource Laboratory) compatible format from HYSPLIT.

2.5 In Situ and Satellite Data

The in-situ measurement data for NOx and CO are obtained from the CPCB website for the Delhi location. TROPOMI total column NOx product from the Sentinel 5 Precursor (S5P) satellite of 2019 and CO Multispectral surface mixing ratio data from MOPITT during 2018 are utilized for comparing PSCF and CWT results for these pollutants (Fig. 2).

2.6 Potential Source Contribution Function

To identify source areas, PSCF values are computed by analyzing trajectory transport pathways (Polissar et al., 1999; Wang et al., 2006). Using the HYSPLIT 4 model and GDAS meteorological data, seven-day backward trajectories of air masses were calculated over Delhi (28.7296° N, 77.1666° E) at 500 meters above ground level (AGL). These trajectories represent the movement of air parcels, with each endpoint indicating the central location of an air parcel at a specific time. The study area was divided into grid cells measuring 0.25° × 0.25°, denoted by grid indices i and j. To calculate the PSCF for a specific grid cell, the number of trajectory endpoints terminating in that cell, represented by n_{ij}, is considered. A 50th percentile cutoff criterion was applied, and the number of endpoints for the same cell was determined when the corresponding samples exhibited concentrations higher than the criterion value, represented as m_{ij}. The PSCF value for the ijth cell is then defined as the ratio of m_{ij} to n_{ij}. The PSCF analysis involves calculating backward trajectories of air masses and quantifying the number of trajectory endpoints within each grid cell. The PSCF value for a particular cell provides information about the likelihood of that cell being a source region based on the concentration levels observed in the corresponding samples:

$$\text{PSCFij} = \frac{m_{ij}}{n_{ij}}$$

The arbitrary weight function (W_{ij}) was multiplied with PSCF values to remove the uncertainties in cells with small values of m_{ij} and to reflect the uncertainty in the values for these cells in a better way (Zeng & Hopke, 1989). The following weighting functions are applied on PSCF:

$$W_{ij} = \begin{pmatrix} 1.0 & \text{When}\,100 < n_{ij} \\ 0.7 & \text{When}\,60 < n_{ij} < 100 \\ 0.4 & \text{When}\,20 < n_{ij} < 60 \\ 0.2 & \text{When}\,n_{ij} < 5 \end{pmatrix}$$

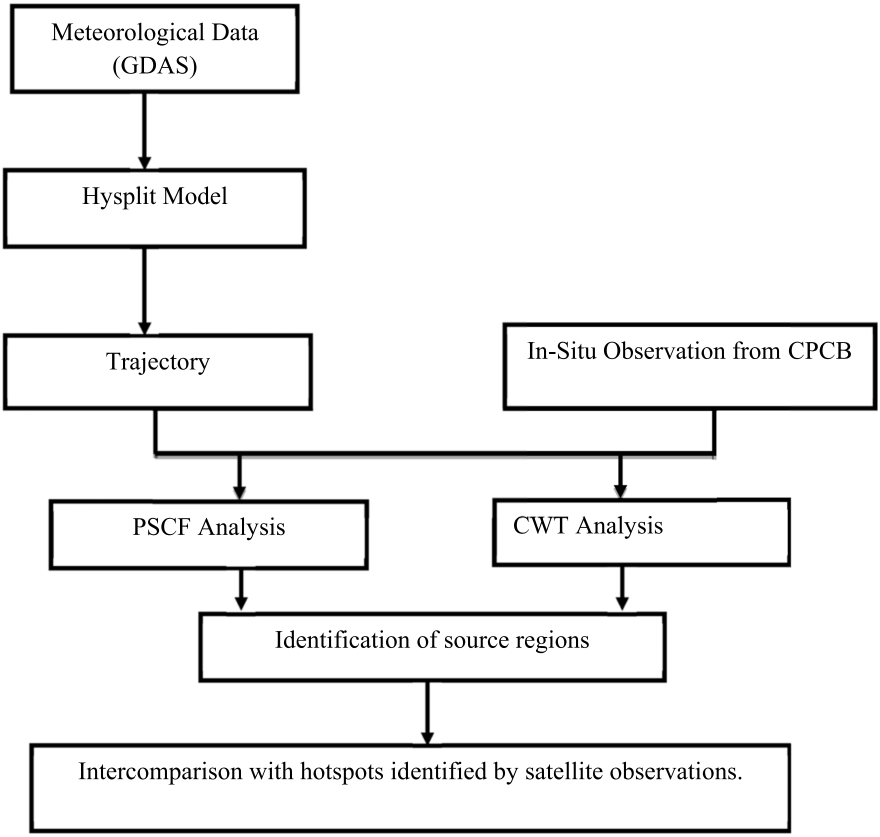

Fig. 2 Methodology flow chart

2.7 Concentrated Weighted Trajectories

In concentration weighted trajectories (CWTs), each square on a grid gets a weighted amount by averaging the sample concentrations linked to the paths that went through that square. (Jeong et al., 2011). It is calculated using the formula.

$$C_{ij} = \frac{1}{\sum_{l=1}^{M} \tau_{ijl}} \sum_{l=1}^{M} C_l \tau_{ijl}$$

In this formula, C_{ij} represents the average weighted amount of pollution in a specific grid cell (*ij*). The index l stands for each trajectory, *M* is the total number of trajectories, C_l is the concentration when a trajectory arrives, and τ_{ijl} is the time spent by a trajectory in that grid cell. The area is divided into small grid cells, and high C_{ij} values mean that there are higher pollutant concentrations in that cell. The CWT method, like PSCF, uses a special method to handle cases where there is not much data (small n_{ij} values). The CWT is useful because it not only shows where potential sources are but also tells us how much they contribute compared with each other. PSCF, on the other hand, mainly shows where potential sources are located.

3 Results and Discussion

3.1 Premonsoon PSCF and CWT

Possible source regions for augmented pollutant levels at the receptor site are highlighted by concentration weighted trajectory (WCWT) and weighted potential source contribution function (WPSCF) maps. Figures 3 and 4 show the source regions of CO and NOx, respectively, during the pre-and postmonsoon seasons identified using PSCF and CWT methods. Various colors represent the contribution levels of potential source areas, where red and green depict the highest and lowest contributions, respectively. Figs. 3a, 4a depict WPSCF maps of CO and NOx over Delhi during the premonsoon season. Premonsoon WCWT maps for CO and NOx also identify the same regions as source locations. High concentrations are observed over Delhi during the months of March to May, which is attributed to vehicular emissions and local sources (Sharma et al., 2016; Sharma & Mandal, 2018). (Sahu et al. (2015)) suggested that pollutant concentrations remain slightly lower during the premonsoon months (March, April, and May) compared with postmonsoon months (September, October, and November), which is attributed to the convective updraft motion of pollutants caused by the higher planetary boundary layer (PBL) height.

3.2 Postmonsoon PSCF and CWT

Figs. 3b, d and 4b, d highlight the potential source locations of CO and NOx pollution over Delhi during postmonsoon. Punjab, Haryana, western Uttar Pradesh, and part of Pakistan presented elevated values for WPSCF and WCWT of CO and NOx. The burning of crop residue typically commences in the northern states of India during the early part of the second half of October, extending for a duration of six to eight weeks for Kharif crops (Awasthi et al., 2010, 2011). Stubble burning releases large amounts of smoke and pollutants into the air, including CO and NOx, which can be transported by wind to the Delhi region. Other meteorological factors, such as wind patterns, temperature inversions, and atmospheric stability, also influence the transport and accumulation of pollutants (Nair et al., 2020).

The WCWT value for NOx was found to be a maximum of 86 ppb during the premonsoon season, while its value increased to 150 ppb in the postmonsoon season, and the value for CO was found to be a maximum of 1.5 mg/m^3 during the premonsoon season and reached 3 mg/m^3 during the postmonsoon season.

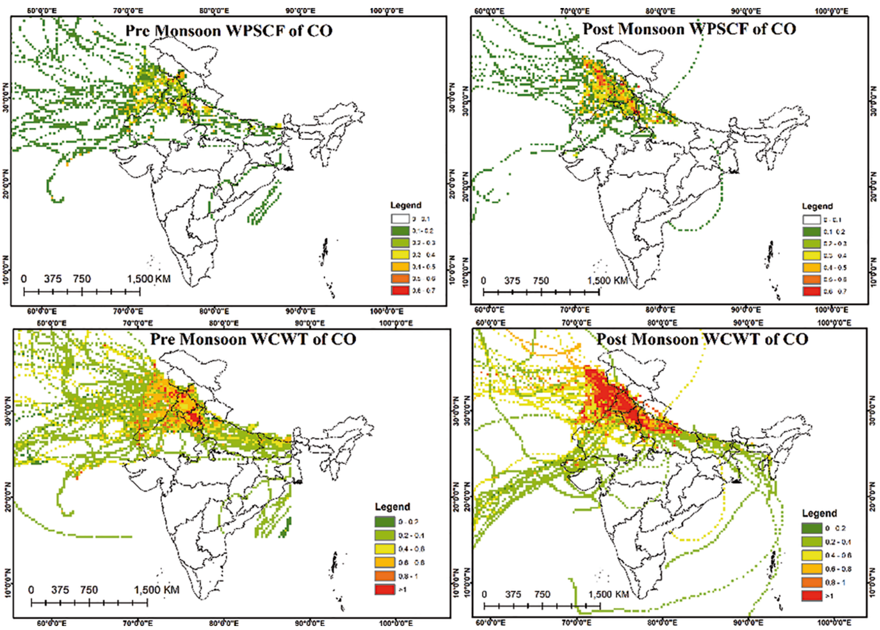

Fig. 3 Weighted potential source contribution function (WPSCF) and concentration weighted trajectory (WCWT) analysis of CO during the pre-and postmonsoon seasons in 2018

3.3 Diurnal Seasonal Variability of NOx and CO

Figure 5 shows the diurnal seasonal fluctuations in CO and NOx during the study period in both the premonsoon and postmonsoon seasons. To capture the diurnal variations, the hourly average values are further averaged for each month and specific season. The findings reveal that the diurnal and seasonal variations exhibit a bimodal distribution. The peaks for both pollutants are notably higher during office/rush hours in the morning and evening than in the evening, especially around 20:00 h, when more pronounced peaks are observed. The bimodal distribution of diurnal variations in CO and NOx may be attributed primarily to vehicular emissions, driven by factors such as traffic density, boundary layer mixing processes, and chemical reactions within the atmosphere. Regarding seasonal variations, both pollutants showed elevated and reduced concentration levels during the post-and premonsoon seasons, respectively. The winds are northwesterly and the wind speed is relatively low during the postmonsoon season, which favors high level of air pollution over northern India. Additionally, in the postmonsoon season, the atmospheric boundary layer remains relatively shallow, restricting the vertical dispersion of pollutants and consequently resulting in increased surface concentrations. NOx and CO exhibit time-dependent variations that provide valuable insights into local pollution conditions (Al-Jeelani, 2014; Sharma & Mandal, 2018).

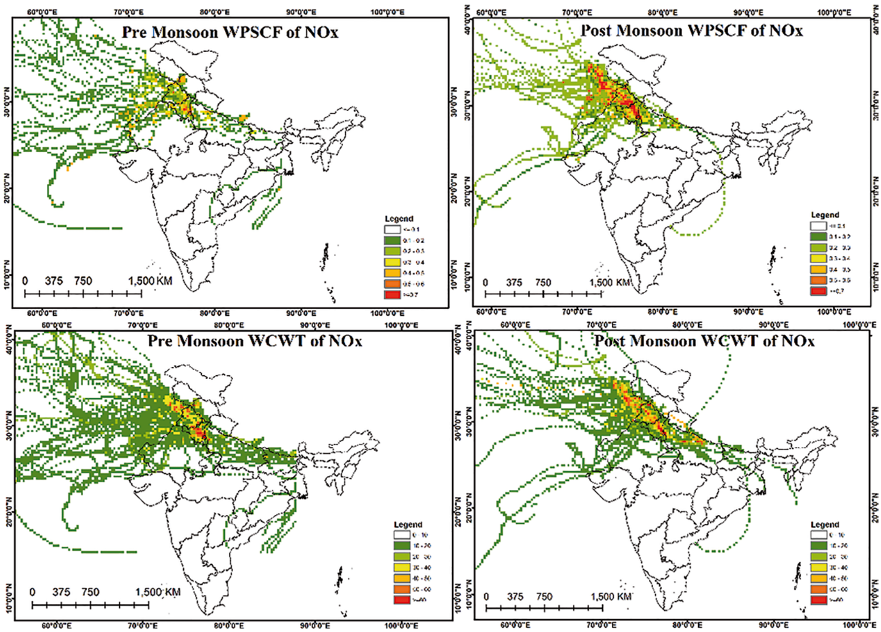

Fig. 4 Concentration weighted trajectory (WCWT) and weighted potential source contribution function (WPSCF) analysis of NOx during the pre-and postmonsoon seasons in 2018

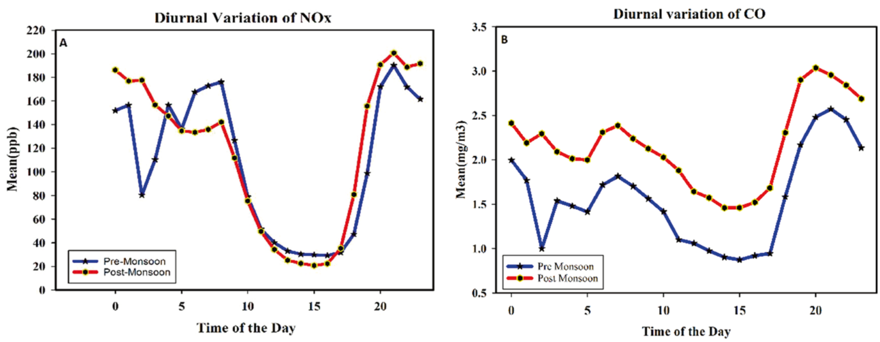

Fig. 5 Diurnal variations of (**a**) NOx and (**b**) CO during the pre-and postmonsoon seasons

3.4 Satellite Observation

The results of the WPSCF and WCWT analyses for identifying source regions were compared with satellite observations of fire counts and air pollutants. Fig. 6a shows that during the premonsoon season, Punjab had 3243 recorded fire counts with a confidence interval greater than 30. This count increased to 12,667 during the postmonsoon season. In Haryana, during the premonsoon season, there were 1003 fire counts, and this number increased to 1745 in the postmonsoon season. Our analysis

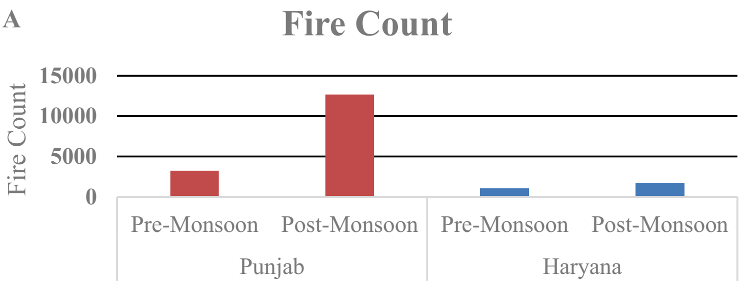

Fig. 12.5 (continued)

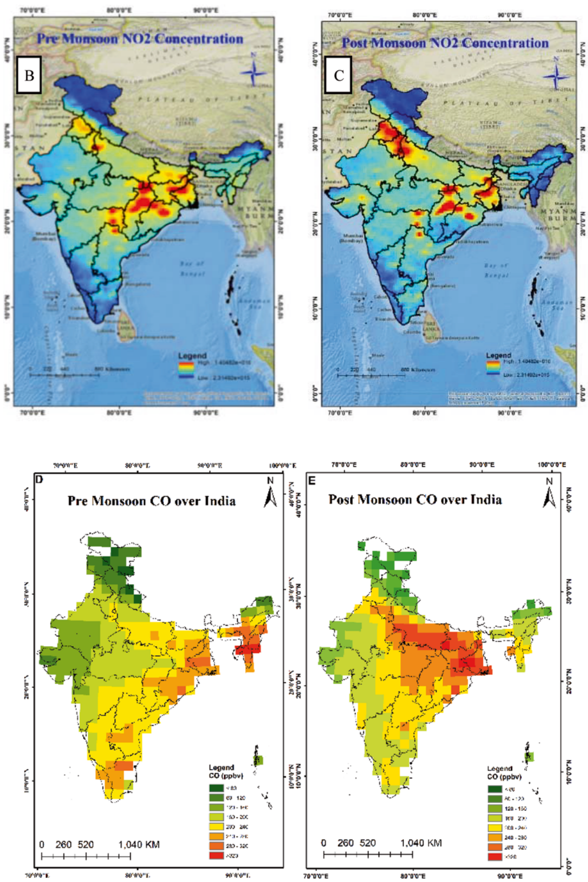

Fig. 6 (**a**) Fire count, (**b**, **c**) surface CO distribution over the Indian region, and (**d**, **e**) total column NO_2 distribution over the Indian region during the pre-and postmonsoon seasons in 2018

of MODIS fire data reveals that fire events during the postmonsoon season peak from October 20 to November 20 when farmers harvest their crops and burn the residue (Sahu et al., 2015). Figure 5b, c clearly depict the increase in NO2 levels in the Sentinel 5P satellite data from the premonsoon season to the postmonsoon season. This rise is attributed to fire events that occurred in the postmonsoon season over Punjab and Haryana. These data support the findings of this study. Both the WPSCF and WCWT analyses identify almost the same areas as the source regions of CO for the aforementioned season. Fig. 6d, e displays the MOPITT-derived surface mixing ratio of CO. During the pre-and postmonsoon seasons, it clearly indicates the prevalence of CO in the Delhi region: CO surface mixing ratios increased during the postmonsoon period with respect to the premonsoon period over Delhi and nearby regions.

4 Conclusion

HYSPLIT trajectory-based WPSCF and WCWT analyses were carried out to identify potential source regions responsible for high CO and NOx levels in the Delhi region. PSCF employs backward trajectory analysis and determines the probable source locations, while CWT assigns concentrations at the receptor site to corresponding trajectories, facilitating source strength analysis.

The elevated pollutant concentration during the postmonsoon period is attributed primarily to the significant amount of stubble burning in Punjab, Haryana, Uttar Pradesh, and part of Pakistan. This practice releases a substantial amount of pollutants, which are then transported to downwind regions, resulting in poor air quality at the receptor location. WPSCF analysis reveals that north Indian states such as Punjab and Haryana are major source regions for NOx and CO over New Delhi, mainly during postmonsoon. WCWT reveals similar source regions during premonsoon and postmonsoon seasons, with higher pollution levels over source locations during the postmonsoon season.

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Air Quality Dynamics in North India

Shefali Juyal, Suman Naithani, and Monica Gangopadhyay

1 Introduction

In numerous cities, India has experienced a significant surge in urbanization and industrialization over the last 20 years. The process of urbanization has brought both favorable and adverse impacts on air quality in various cities around the world. The utilization of fossil fuels and their derivatives has experienced a substantial surge in developing nations due to the process of modernization and industrialization (Gautam et al., 2016). Human-caused releases of pollutants in urban areas have the potential to significantly affect atmospheric composition, chemistry, and life cycles in downwind regions (Usha, 2008). As a result, developing countries face a significant challenge in managing atmospheric pollution, especially in rapidly expanding megacities.

A WHO report (2012) highlighted the alarming implications of this challenge, revealing that approximately two million individuals die prematurely each year as a result of air pollution. Furthermore, the detrimental impact of air pollution is evident in developing nations, where a considerable portion of the population experiences respiratory ailments, cardiovascular complications, lung infections, and even cancer. This emphasizes the pressing requirement for efficient approaches to regulate and alleviate the negative consequences of atmospheric pollution, particularly in light of the rapid urbanization and industrial growth occurring in these regions. India's rapid economic growth and industrialization have resulted in the creation of vastly contaminated air on the planet. According to projections, it is anticipated that the air quality will continue to worsen, resulting in a projected 24% rise in premature mortality associated with PM2.5 by the year 2050 in comparison with 2015

S. Juyal · S. Naithani (✉) · M. Gangopadhyay
Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India
e-mail: suman_geu_naithani@geu.ac.in

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(GBD MAPS Working Group, 2018; Brauer et al., 2019). According to a study conducted by Chowdhury et al. (2020), the Global Exposure Mortality Model (GEMM) has revealed a noteworthy increase of around 47% in premature mortality linked to PM2.5 exposure in India from 2000 to 2015.

Furthermore, apart from the apprehensions regarding particulate matter, it is anticipated that the levels of surface ozone (O_3) will rise as a result of the escalating industrial emissions and the elevated temperatures linked to climate change. This escalation puts additional pressure on agricultural yields and public health, compounding the problems posed by air pollution (Avnery et al., 2011; Silva et al., 2017). As India grapples with the consequences of its growth, addressing these complex interactions between industrialization, climate change, and air quality becomes imperative to protect the environment and public welfare.

2 Material & Methods

2.1 Sources

Air pollution is caused by a number of factors (Fig. 1), often stemming from human activity. The main reasons for air pollution include:

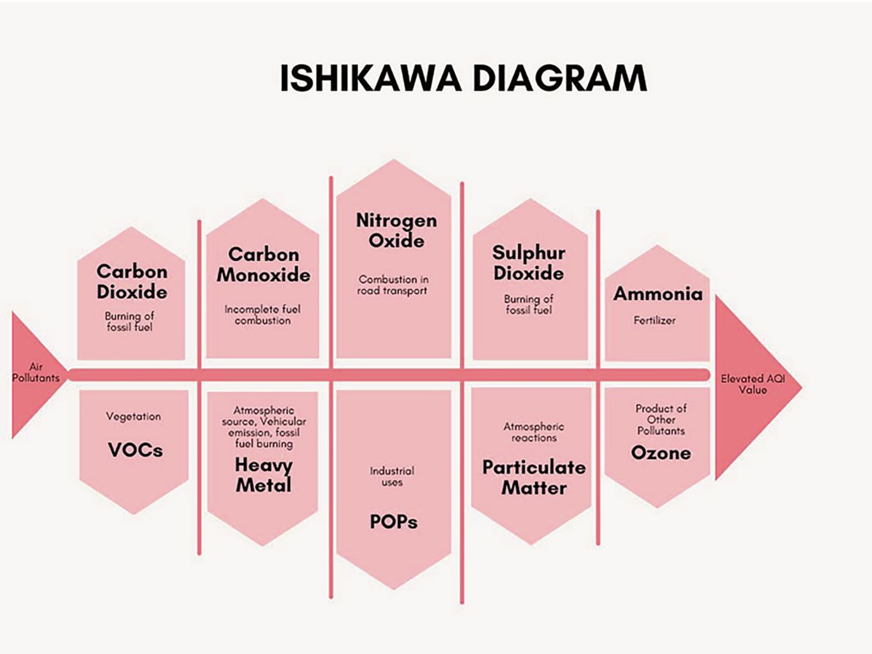

Fig. 1 Ishikawa diagram of factors affecting air quality dynamics

1. Vehicular Emission: The release of air pollutants, including nitrogen oxides, carbon monoxide, and particulate matter, occurs through the internal combustion engines found in cars, trucks, and various other vehicles.
2. Industrial Emission: Pollutants such as sulfur dioxide, particulate matter, and volatile organic compounds are emitted as by-products of manufacturing processes in factories and industrial facilities.
3. Power Generation: The process of burning fossil fuels, namely coal, oil, and natural gas, for the purpose of electricity production leads to the release of pollutants such as sulfur dioxide, nitrogen oxides, and carbon dioxide.
4. Agricultural Practices: Agricultural activities contribute to air pollution by releasing ammonia from fertilizers, methane from livestock and pesticides.
5. Stubble burning and Deforestation: The act of deforestation and the practice of biomass burning contribute significantly to the emission of particulate matter and carbon into the atmosphere. This occurs when forests are cleared and biomass is burned for agricultural or other purposes.
6. Waste Disposal: The mismanagement of waste, particularly through improper disposal and burning, poses a significant threat to air quality. Harmful pollutants are released into the atmosphere as a result, especially when waste materials such as plastics are involved.
7. Construction and Demolition: Dust and particulates generated during construction and demolition activities can contribute to local air pollution.
8. Domestic heating and Cooking: Using solid fuels (wood, coal, etc.) for domestic heating and cooking can release pollutants such as particulate matter and carbon monoxide.
9. Natural Sources: Although human activity plays a major role, the air can also be contaminated by pollutants from natural sources like fires, volcanic eruptions, and dust storms.
10. Chemical and Industrial processes: Some chemical production processes release pollutants directly into the air, thereby contributing to air pollution.

2.2 Air Pollutants

The major air pollutants present in the air are of following types:

- Particulate Matter (PM): Particulate matter refers to tiny particles that are suspended in the air. These particles are categorized based on their size, with PM10 referring to particles that are 10 micrometers or less in diameter, and PM2.5 referring to particles that are 2.5 micrometers or less in diameter. The sources of these particles include vehicle emissions, industrial processes, as well as natural sources such as dust and forest fires.
- Ground-level ozone (O_3): Ground-level ozone is a type of pollutant that is formed as a result of chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the presence of sunlight. This secondary pollutant is mainly generated from emissions produced by vehicles and industrial activities.

- Nitric oxide (NO_2): nitrogen oxide gas produced during combustion processes, especially in vehicles and power plants. NO_2 contributes to respiratory problems and the formation of ground-level ozone.
- Sulfur Dioxide (SO_2): Sulfur dioxide is a gas that is generated when sulfur-containing fossil fuels like coal and oil are burned. It is primarily emitted by power plants and industrial facilities. The inhalation of SO_2 can result in respiratory issues and the creation of acid rain.
- Carbon Monoxide (CO): Carbon monoxide (CO) is a colorless and odorless gas that is produced when fossil fuels are incompletely burned. Vehicle emissions are a major contributor to CO levels. High concentrations of CO can be detrimental to health and can impede the body's ability to transport oxygen.
- Volatile organic compounds (VOCs): Volatile organic compounds (VOCs) are organic chemicals that have the ability to evaporate into the atmosphere. They originate from sources such as vehicle exhaust, industrial processes, and certain consumer products. VOCs contribute to the formation of ground-level ozone and can have negative impacts on human health.
- Lead (Pb): Although its levels have decreased due to regulatory efforts, lead may still be present in the air from past use in gasoline and industrial activities. Lead exposure can lead to neurological and developmental problems, especially in children.

3 Review of Literature

The substantial expansion of industrialization and urbanization in India, the world's second most populous country, has led to a significant increase in anthropogenic emissions. According to IHME (2013), outdoor particulate matter (PM) emerged as the seventh leading cause of death in India between 1990 and 2010. India, 50% of which is in the residential sector (Lelieveld et al., 2015). The situation in New Delhi, the capital of India, is cause for alarm due to the extremely high levels of PM2.5. In 2014, the annual concentration of PM2.5 in New Delhi was 153 μg/m^3, which is more than 10 times higher than that of Washington DC (WHO, 2014). Taking measures to control PM2.5 concentrations can have a significant impact on reducing mortality rates. According to a study by Sahu and Kota (2017), meeting the World Health Organization's recommended annual average PM2.5 standard of 10 μg/m^3 could potentially save 41 out of every 100,000 lives in Delhi.

3.1 Emission of Vehicles

There is a direct link between the road transport system and air pollution in urban areas. Vehicle emissions are affected by factors such as vehicle speed, distance traveled (vehicle kilometers), vehicle age, and emissions.

Vehicles have become a significant source of air pollution in urban regions of India. The pollution caused by vehicles is a result of emissions like carbon monoxide (CO), unburned hydrocarbons (HC), lead (Pb), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and suspended particulate matter (SPM). These emissions primarily originate from exhaust systems.

There is a direct link between the road transport system and air pollution in urban areas. Vehicle emissions are affected by factors such as vehicle speed, distance traveled (vehicle kilometers), vehicle age, and emissions. The rapid increase in the number of vehicles is the main cause of the deterioration of air quality in urban areas. Vehicular pollution plays a significant role in this, accounting for 70% of the total pollution in Delhi, 52% in Mumbai, and 30% in Calcutta, according to several studies (C.P.C.B., 2003; Gokhale and Patil, 2004).

According to a study conducted by Babu and Damodar (2017), the motor vehicle population in India has witnessed an annual growth rate of approximately 10% during the past 10 years. A significant proportion of Indian motor vehicles are concentrated in urban centers, with an alarming statistic showing that 32% of these vehicles are densely occupied in metropolitan areas alone. For example, Delhi already boasts over 2.6 million registered motor vehicles, with around 600 new vehicles being registered every day.

Chandigarh has the highest vehicle density in India with 878 registered motor vehicles per thousand people, according to the 2016 State of the Environment Report. Vehicle emissions are a major contributor to background urban air pollution. Research by Bhargava et al. in 2018 revealed a more than twofold increase in vehicular greenhouse gas emissions in Chandigarh between 2005 and 2011.

3.2 Industrial Activities

Industrial processes release significant amounts of organic compounds, carbon monoxide, hydrocarbons, and various chemicals into the atmosphere. A substantial volume of carbon dioxide is a key contributor to the greenhouse effect. The current problem lies in the excessive amount of GHG gases along with particulate matter (PM) contributing to recent climate change.

The cement industry is responsible for approximately 2% of global energy consumption and contributes to around 5% of global manmade carbon dioxide emissions from cement production, as estimated by Chandrasekhran in 1998. Dust generation is a notable environmental consequence of cement production, occurring during transportation, storage, grinding, and packaging processes, as highlighted by Chaurasia et al. in 2013 and Gupta et al. in 2002. In dry climates, atmospheric dust becomes a major contributor to air pollution.

3.3 Agricultural Activities

Every year, the burning of agricultural residue in the Indo-Gangetic Plains (IGP) results in the release of substantial quantities of reactive nitrogen and various other pollutants into the atmosphere. The act of burning biomass in forest fires, prescribed burning, and agricultural burning is widely recognized for its contribution to the emission of significant amounts of pollutants into the atmosphere. Consequently, this leads to the deterioration of air quality at both local and regional levels (Scholes et al., 1996; Andreae and Merlet, 2001; Freitas et al., 2005; Arola et al., 2007).

According to Yadav et al. (2017), research has been conducted globally and has investigated various aspects of biomass burning. Every year, the burning of biomass is believed to result in the depletion of around 500–1000 million hectares of open forest and savanna. In addition, approximately one million hectares in northern latitudes and four million hectares in tropical and subtropical forests are also affected by this activity.

About 20–25% of crop residues produced in India are burnt in open fields as reported by Ravindra et al. (2019). This malpractice has a detrimental impact on the air quality in the Indo-Gangetic plains of India.

Delhi, situated at an elevation of 216 m above sea level, is adjacent to Punjab and Haryana, two significant agricultural states. In these states, the practice of burning crop residues after the Kharif harvest season (October–November) is routine. Unfortunately, this period coincides with weak surface northwesterly winds, resulting in stagnant pollution and subsequent deterioration of air quality. The extensive plumes of pollutants emitted during this burning process can travel vast distances, spanning thousands of kilometers downwind (Chen et al., 2017). It is worth noting that the intensive burning of crop residues primarily impacts short-term changes in particle concentrations rather than long-term alterations, as observed by Wu et al. (2017).

3.4 Thermal Plants

In 2008, the World Health Organization (WHO) reported that coal particulate pollution is thought to shorten the life expectancy of approximately 1,000,000 people worldwide each year. Despite the various uses of fly ash, a substantial part (at least 70%) is still disposed of in lagoons and landfills, leading to adverse consequences such as air and water pollution.

According to a 2014 study by Vasistha, coal-fired thermal power plants are widely recognized worldwide as major contributors to environmental pollution. They significantly affect the environment in terms of land use, health risks and air, soil, and water pollution. Discharge of fly ash into water bodies further exacerbates this problem and directly affects the structure and integrity of the aquatic ecosystem.

Currently, carbon dioxide (CO_2) emissions from burning coal account for more than 60% of the increased greenhouse effect. For every ton of coal burned as a fossil fuel, at least one-third of a ton of CO_2 is released into the atmosphere. According to reports, the emission of CO_2 from Indian power plants is estimated to be approximately 0.8–0.9 kg per kilowatt-hour (kWh).

4 Scenario of Air Quality in Various States of India

4.1 Bihar

In Bihar, the primary contributors to air pollution are road dust, vehicle emissions, and the burning of domestic fuel. Additionally, open burning of waste, construction activities, and industrial emissions also play a significant role in exacerbating the pollution levels in the region. Particulate matter was identified as the primary air pollutant in Bihar city, mainly attributed to road dust resuspension, vehicle emissions, construction activities, fossil fuel combustion; open burning of solid waste and transportation of construction materials such as sand and soil. Old vehicle traffic and traffic congestion contribute to elevated NO_2 levels. During the winter, air quality deteriorates significantly, fine particles condense in the lower layers of the atmosphere.

4.2 Delhi

Delhi, the capital city of India, has been facing significant air pollution problems for several years. The urban area encounters a multifaceted interaction of elements that contribute to its substandard air quality, encompassing elevated emissions from vehicles, pollution from industries, ongoing construction projects, the incineration of waste materials, and the burning of agricultural remnants in nearby states. Especially in the winter months, a combination of atmospheric conditions manifests itself, stagnant air, and increased emissions lead to the formation of a thick layer of smog, which causes a drop in air quality. Concentrations of pollutants such as PM2.5, PM10, SO_2, NO_2, and O_3 often exceed recommended levels, posing a major risk to human health.

4.3 Haryana

Haryana is one of the fast-developing states in North India. The population recorded at 25.31 million in the 2011 census shows a distribution of around 29% in urban areas (Kaushik et al., 2006). Cities are distinguished by the presence of small-, medium-, and large-scale industries. According to research by Bhanarkar et al. (2002), primary urban centers in Haryana include Sonipat, Panipat, Gurugram, Faridabad, Rohtak, and Rewari. The Haryana sub-region, the second largest within the National Capital Region (NCR), includes 55 urban centers and 2413 villages covering an area of 13,413 km^2. The rapid growth of the Haryana sub-region within the NCR is leading to substantial changes in the quality of the environment.

4.4 Himachal Pradesh

Himachal Pradesh encompasses a diverse topography that is known as a biodiversity hotspot. Himachal Pradesh is renowned for its diverse range of forest types, consisting of eight distinct categories and 38 sub-types as classified by Champion and Seth. The climate in this state exhibits a remarkable variation, spanning from semi-tropical to semi-arctic conditions. The primary sources of emissions in Himachal Pradesh include road transport, industrial combustion, and the domestic cement industry. Emissions of nitrogen oxides (NOx) are mainly related to the road transport sector, while emissions of particulate matter are mainly attributed to industrial combustion, the housing sector and cement plants. Although current emissions are relatively moderate, the lack of adequate control measures could lead to a significant increase in these emissions in the future.

4.5 Jammu & Kashmir

Jammu and Kashmir is a northwestern Himalayan region that has seen an increase in air pollution levels over the past decade, mainly due to growth in traffic and industrial activities. In Jammu and Kashmir, tourism is the predominant sector, previously considered a "smokeless" industry with minimal environmental impacts, but according to a current report, its potential for adverse impacts is increasingly recognized (Jehangir et al., 2011).

4.6 Punjab

Located in the western Indo-Gangetic plain, Punjab is known as the "breadbasket" of India due to its position as the most fertile region in the region. Although predominantly an agrarian economy, Punjab has experienced the emergence of various industrial units, ranging from small to large, in key cities like Ludhiana, Amritsar, Mandi-Gobindgarh, DeraBassi, and Rajpura. In their study, Garg et al. (2021) highlighted Ludhiana as a prominent city in Punjab, often referred to as the Manchester of India, due to its diverse industrial landscape encompassing textile, auto parts, food products, bicycle, and steel industries. The Micro, Small and Medium Enterprises (MSME) Report 2014–2015 reveals that Ludhiana district is home to 38,552 registered micro and small units, along with 153 medium and large units. Mandi-Gobindgarh, recognized as the steel city of Punjab, holds a significant presence of the steel industry. The city accommodates approximately 600 industrial units, including over 500 medium- to small-scale metal scrap recycling industries. However, it is unfortunate that these industrial activities in Mandi-Gobindgarh have been reported to contribute significantly to local environmental pollution by Ghosh and Jain (2010) and Gupta et al. (2013).

4.7 Uttar Pradesh

Sharma et al., (2023) conducted a study on Uttar Pradesh, the most populous state in India, and found that it faces a significant mortality rate due to exposure to ambient air. With a population of 227.65 million, Uttar Pradesh is known for its high population density. Moreover, the state has a substantial number of vehicles, reaching 3,529,817 in 2019–2020. It also accommodates 15 industrial areas and boasts various tourist attractions, attracting 535.8 million domestic tourists and 4.74 million foreign tourists in 2019 alone. The research highlights that the major sources of air pollution in NAC UP include vehicles, industries, biomass and waste burning, road dust, and the domestic sector.

4.8 Uttarakhand

In Uttarakhand, the primary contributors to air pollution come from emissions produced by both automobile and industrial activities. Escalating levels of air pollution in the region are further exacerbated by development activities associated with the industrialization of the state. Growing urbanization characterized by urban sprawl, a substantial increase in population migration to urban areas, increased consumption patterns, and the prevalence of unplanned urban and industrial emissions together stand as key factors amplifying the environmental challenge.

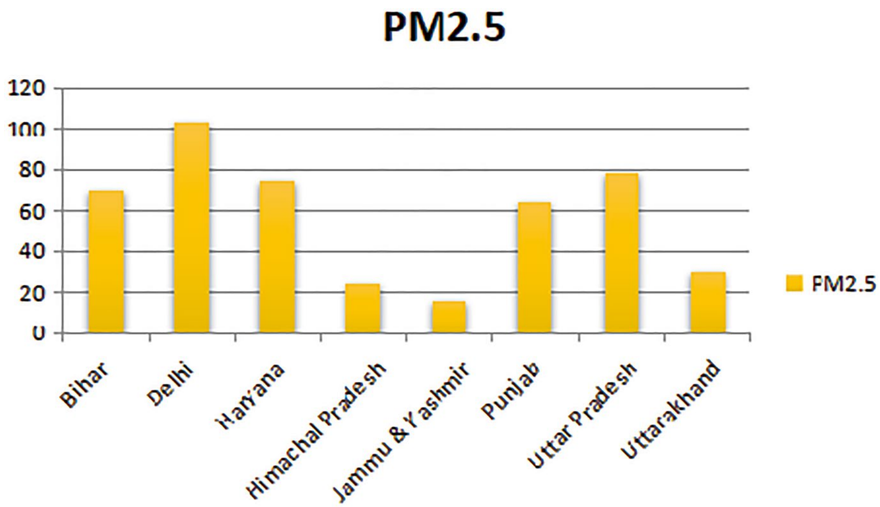

Fig. 2 Comparison of PM2.5 Concentration

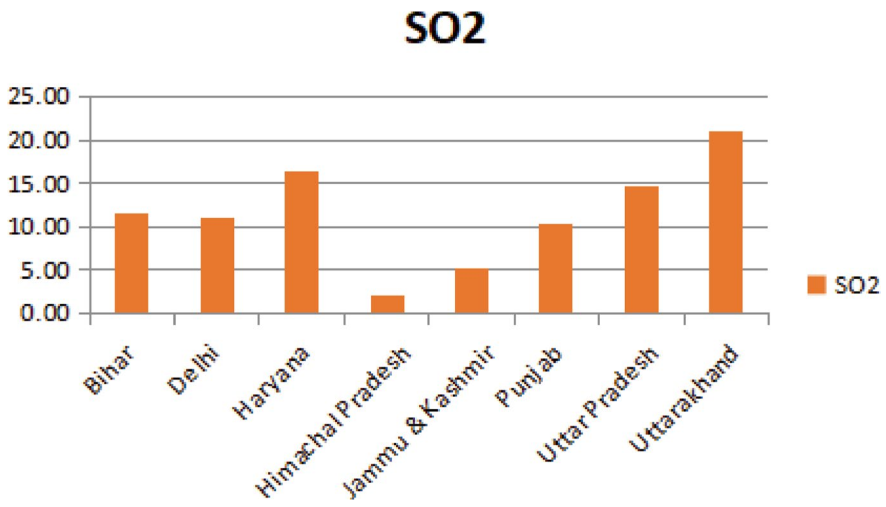

Fig. 3 Comparison of SO_2 Concentration

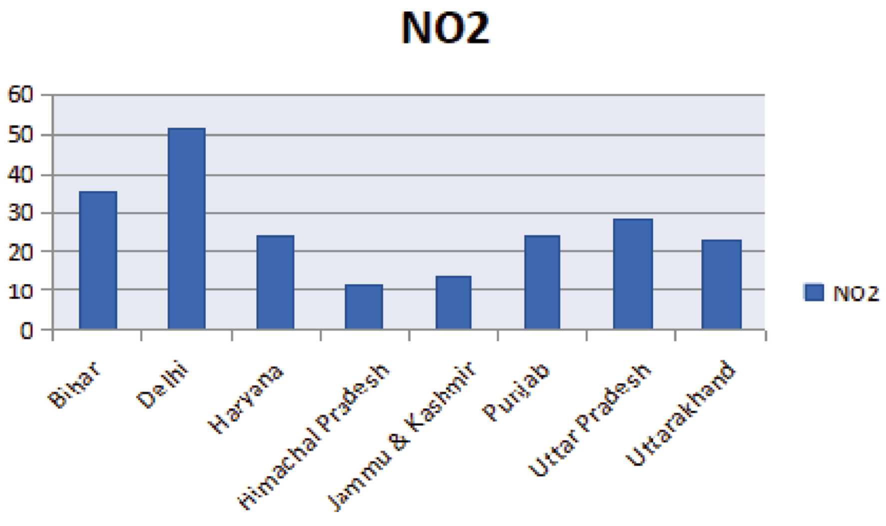

Fig. 4 Comparison of NO_2 Concentration

5 Result and Discussion

After analyzing the concentration levels of PM2.5, SO_2, NO_2, and PM10 in various states across North India, the data shown in Figs. 1, 2, 3, and 4 revealed that:

- The observation derived from Tables 1, 2, 3, and 4 indicates that Delhi exhibits the poorest air quality compared to all the listed states. This can be attributed to

Table 1 Source and Their Percentage of Air Pollution in India

S. No.	Source	Percentage
1	Industrial	51%
2	Vehicular emission	27%
3	Crop (waste) burning	17%
4	Dust & Construction	8%
5	Transport	14%
6	Diesel generator	9%
7	Domestic cooking	7%

Table 2 State average annual $PM_{2.5}$ concentration (μg/m^3) of North India

S. No.	Region name	1998	2000	2005	2010	2015	2020
1	Bihar	54.6	60.4	66.4	75.2	78.2	83.9
2	Delhi	80.0	90.8	101.1	126.9	112.1	111.3
3	Haryana	53.8	62.9	72.6	90.2	84.2	83.3
4	Himachal Pradesh	18.6	25.9	23.4	25.5	27.2	26.1
5	Jammu & Kashmir	13.5	17.5	15.1	16.3	16.2	15.3
6	Punjab	47.3	57.7	63.8	76.3	73.7	70.9
7	Uttar Pradesh	63.0	68.2	77.7	88.6	85.3	88.2
8	Uttarakhand	23.4	31.6	28.3	31.8	34.9	31.0

elevated levels of vehicular emissions, industrial activities, over population, crop burning in nearby states, and adverse meteorological conditions (Table 5).

- In the provided tables, a noteworthy trend emerges when comparing data from 1998 to 2020. Specifically, during the unprecedented events of 2020, marked by the global COVID-19 pandemic, a substantial decline in pollutant levels is evident. This occurrence can be attributed to the widespread lockdown measures implemented during that period, resulting in a complete cessation of activities that typically contribute to air pollution.
- Jammu and Kashmir recorded the lowest concentration of PM2.5 unlike Delhi which showed the highest levels among the areas surveyed.
- SO_2 concentration in Himachal Pradesh was lowest and highest in Uttarakhand.
- Himachal Pradesh NO_2 concentration was the lowest recorded while Delhi recorded the highest.
- The PM10 concentration of Himachal Pradesh was found to be the lowest and Delhi was the highest.
- The concentration of pollutants was mainly observed to be higher in winter seasons (Fig. 5).

6 Conclusion

Based on the data provided, it can be inferred that respirable suspended particulate matter (RSPM) levels are significantly elevated.

Table 3 State average annual SO_2 concentration (μg/m^3) of North India

S. No.	Region name	1998	2000	2005	2010	2015	2020
1	Bihar	9.5	16.4	11.9	7	13.11	11.45
2	Delhi	6	7.6	8.1	10.5	17.54	16.76
3	Haryana	13.72	25.41	15.61	12.66	15.5	14.86
4	Himachal Pradesh	1.51	1.30	1.74	2.85	3.5	2.2
5	Jammu & Kashmir	6.2	6.47	6.05	6.44	3.5	3.02
6	Punjab	5.25	15.63	14.87	10.1	8.62	6.93
7	Uttar Pradesh	20.62	20.38	12.9	12.45	11.37	10.02
8	Uttarakhand	16	18	22	28	25.9	15.51

Table 4 State average annual NO_2 concentration (μg/m^3) of North India

S. No.	Region name	1998	2000	2005	2010	2015	2020
1	Bihar	21.5	20.5	27.5	40	57.4	42.36
2	Delhi	40.12	44	46.55	55	71.96	52.18
3	Haryana	25.65	10.04	13.46	21	34.68	39.76
4	Himachal Pradesh	9.45	6.91	11.98	15	16.54	9.1
5	Jammu & Kashmir	11.65	13.05	15.06	14.31	16.55	14.06
6	Punjab	8.75	30.28	37.07	25.7	22.59	17.96
7	Uttar Pradesh	22.26	22.34	32.88	29.88	28.82	32.36
8	Uttarakhand	13.99	18.43	26.02	30	26.52	21.79

- The primary cause of pollutant generation was consistent across all cities monitored, with vehicles and automobiles identified as the main contributors.
- Increased efforts are needed to make air quality monitoring a national priority by promoting increased awareness and compliance with specific laws and regulations.
- Using energy-efficient commodities is essential because they not only contribute to energy savings, but also have the advantage of minimizing negative environmental impacts.
- Further strengthening of current policies and strategies is necessary to achieve more positive and effective results.
- People should be encouraged to opt for public transport instead of relying on private vehicles.
- Regular evaluations of vehicles should be carried out with a focus on air pollutant emissions and vehicles meeting the necessary standards must be given proper certification.
- There is a vital need to increase people's awareness of the health effects of air pollution. The goal of this effort is to encourage individuals to take air quality seriously and prioritize breathing safer and cleaner air.

Table 5 State average annual PM_{10} concentration (μg/m^3) of North India

S. No.	Region name	1998	2000	2005	2010	2015	2020
1	Bihar	161.99	150	224.6	181	199.23	156.92
2	Delhi	150.14	165	373	261	295	250
3	Haryana	129.58	125.86	126.48	173.33	173.59	193.11
4	Himachal Pradesh	73.92	75.34	9.74	87.86	125.28	49.3
5	Jammu & Kashmir	90.51	102.24	105.86	111.68	125.28	104.06
6	Punjab	123.11	130.92	232.93	172.3	121.30	109.63
7	Uttar Pradesh	140.32	160.26	168.38	175	178.20	200.22
8	Uttarakhand	100.43	105.38	121.02	162	145.14	106.03

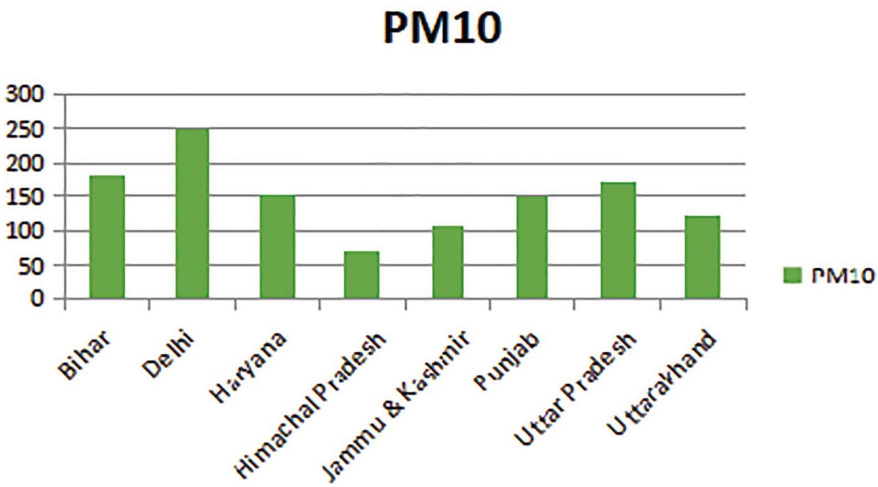

Fig. 5 Comparison of PM10 Concentration

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Factor Militating Against Solid Waste Management in Africa

Jonathan K. Moses, Suman Naithani, and Shazia Akhtar

Abbreviations

GDP	Gross Domestic Product
ISWA	International Solid Waste Association
SDG	Sustainable Development Goal
SWM	Solid Waste Management

1 Introduction

Due to its size and population, Africa is the second largest continent in the globe. Across 62 political jurisdictions with a combined population of more than 1 billion people, the region between 9.10210 N and 18.28120E measures 30,221,532 km^2 (Getahun et al., 2012).The Sahara, the world's biggest desert, is located to the north. Tropical rainforests dominate much of the equatorial region, while further south, grassy, flat highlands give place to coastal lowlands (Orhorhoro & Oghoghorie, 2019). Africa is now ruled by a variety of regimes, ranging from military to democratic, but the goal for economic growth and poverty elimination is what is causing change on the continent as a whole through which solid waste generation in Africa is a perpetual problem in all countries. This problem has suggested to the fact that solid waste is not correlating with environmentally sustainable management practices in Africa. As it is being established that solid waste affects global population, as population increases waste generation will continue to increase due to the high

J. K. Moses · S. Naithani (✉) · S. Akhtar
Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India
e-mail: suman_geu_naithani@geu.ac.in

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increase in any nation's population. Example of such is Nigeria, in West Africa. People's consumption and use of solid matter are recognized to be impacted by internationalization, which ultimately leads to significant solid waste production (Fakunle & Ajani, 2021).

The term "solid waste" describes the undesired and wasted stuff that comes from communal activities on a daily basis. It comprises a variety of waste kinds, including commercial, industrial, agricultural, and household garbage (Al-Taai, 2022). Consumption and use of solid matter are recognized to be impacted by internationalization, which ultimately leads to significant solid waste production. Waste material (SW) generation increases at the same pace as a nation's rate of development. With 38% of the population, Africa is considered the least developed continent on the globe.

African nations are rapidly developing, with an annual growth rate of 4%, despite the fact that this is low compared to many other nations in the world. African nations are currently dealing with enormous amounts of Municipal Solid Waste (MSW), which directly affects human health, safety, and the environment (Godfrey, 2019). The generation of waste has increased globally, and MSW is just one of several significant waste forms. The population distribution across the continent is shown in Fig. 1, together with the corresponding total economic output or gross domestic product (GDP), which indicate an upward trend in Africa.

This shows the population distribution across the continent and the associated gross domestic product (GDP) which point toward the progressive trend in Africa. Table 1 shows the Population and Gross Domestic Trends across Africa Country Population (millions) GDP (PPP) Per capita (USD). However, in this region, garbage, which is frequently a result of industrial development, is still poorly managed, and the potential for related revenue production is not fully realized. African cities

Fig. 1 Collection site of MSW

Table 1 African Countries Population Growth and Their Gross Domestic Product

Countries of population Gross			Domestic Product(GDP)			
↓→	2010	2011	2012	2010	2011	2012
Egypt	80.4	82.6	82.3	6343	6454	6544
Sudan	40.1	44.6	33.5	2178	2682	2544
Nigeria	158.3	162.3	170.1	2419	2582	2720
Ghana	24	25	25.5	2732	3112	3305
Cameron	20	20.1	2193	2193	2274	2366
Ethiopia	85	87.1	1041	1041	1119	1190
Kenyan	40	41.6	1680	1680	1740	1802
Tanzania	43.2	46.2	1392	1392	1469	1566
Angola	19	19.6	20.9	5748	5923	6346
Zambia	13.3	13.5	13.7	1516	1614	1721
South Africa	49.9	50.5	51.1	10,562	11,028	11,375

function as the hub of the majority of socioeconomic activity, but it implies that the ineffective collection, management, disposal, and recycling of solid waste detracts from the allure of several African towns. In order to have a general understanding of the investment potentials of the created garbage, this article tries to identify and define the solid waste generation in Africa.

Source Population Reference Bureau 2010, 2011, 2012 http://www.gfmag.com. 2013.

The International Solid Waste Association (ISWA) and the UN Environment Programme (UNEP) together released the first Global Waste Management Outlook in 2015 (Godfrey et al., 2012), which emphasized the need for more information on regional trash generation and.

Waste Management Outlook in June 2018 (Godfrey et al., 2020)**.** The Africa Waste Management Outlook describes the current state of waste governance, the associated environmental, social, and economic impacts of waste, as well as the advantages that waste presents through appropriate solutions and financing mechanisms. It also outlines the opportunities that waste provides. The Africa Waste Management Outlook's principal results are condensed in this chapter and contextualized.

2 Types of Solid Waste Generated

Types of solid waste generated in Africa include demolition and construction waste, automotive waste, biological waste (such as agricultural by-products), healthcare industry waste, and electronic waste (Babayemi & Dauda, 2009).

Hazardous wastes, packaging wastes, and marine little materials dumped during leisure, fishing, or personal hygiene activities are occasionally grouped together as healthcare wastes (Fakunle & Ajani, 2021). As was already established, a nation's trash production is influenced by both population and income increase. Nonetheless, income appears to be the primary driver of trash production because nations with high incomes, but fewer populations generate a sizable amount of waste, the volume of garbage produced, and the requirement.

Garbage is produced every day and is referred to as solid waste (SW). It is also frequently referred to as rubbish or junk. All industries are regarded as waste source generators although, in their sectors, trashes are frequently managed separately from other SW since responsible parties are accountable for its management. Residential waste is waste produced by a resident every minute, and the types of trash that are frequently produced are those that are related to daily living. These include hazardous wastes like paint and aerosol spray, as well as paper, tin, bottles, textiles, glass, metals, and e-waste (Table 2).

Table 2 Types of Solid Waste Generated in Africa and Their Sources

Source	Typical waste generators	Types of solid wastes
Residential	Single and multifamily dwellings	Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, metals, ashes, special wastes (e.g., bulky items, consumer electronics, white goods, batteries, oil, tires), and household hazardous wastes.)
Industrial	Light and heavy manufacturing, fabrication, construction sites, power, and chemical plants	Housekeeping wastes, packaging, food wastes, construction and demolition materials, hazardous wastes, ashes, special wastes
Commercial	Stores, hotels, restaurants, markets, office buildings, etc.	Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes
Institutional	Schools, hospitals, prisons, government centers	Same as commercial
Construction and demolition	New construction sites, road repair, renovation sites, demolition of buildings	Wood, steel, concrete, dirt, etc.
Municipal services	Street cleaning, landscaping, parks, beaches, other recreational areas, water and wastewater treatment plants	Street sweepings; landscape and tree trimmings; general wastes from parks, beaches, and other recreational areas; sludge
Process (manufacturing, etc.)	Heavy and light manufacturing, refineries, chemical plants, power plants, mineral extraction and processing	Industrial process wastes, scrap materials, off-specification products, slay, tailings
Agriculture	Crops, orchards, vineyards, dairies, feedlots, farms	Spoiled food wastes, agricultural wastes, hazardous wastes (e.g., pesticides)

3 Trend in Solid Waste Management

Waste collection, treatment, transportation, storage, and eventual disposal are some of the key issues facing metropolitan areas today in Africa. As a result, they have observed a generally deplorable waste system. Poor sanitation conditions are made worse by waste management practices used in underdeveloped nations, especially in Africa, which frequently involve the reckless disposal of waste in isolated locations and near bodies of water(Mecca et al., 2013). Future industrialization in Africa is anticipated to continue at its current rate of growth. However, one of the significant issues is the lack of sufficient infrastructure and suitable land use planning to meet the demands posed by the rate of urban growth, particularly the slums and ghettos in Africa(David et al., 2020). History has demonstrated that due to improper waste management, which had an impact on both the environment and public health, human existence was peaceful and was in harmonious with the environment. Woods, leftover food, vegetables, and other organic materials were the main components of garbage in ancient times (10, 000 BC to 4000 AD).

Woods, crop residues, fruits, and other materials have been the main components of garbage in old period. Trashes back then were purely domestic, making it typically biodegradable (Chidiebere et al., 2018). Because there were no industries and a limited population, there were few wastes produced. There were no such things as waste management processes, and the consumable portion of the trash was fed to animals while the remainder was allowed to rot in the ground. Clay samples used in historical digs have shown that throughout time, garbage from different sources developed stratified strata.

4 Solid Waste Composition

According to several studies, solid waste is produced every day from a wide range of sources, including households, businesses, industries, and municipal operations. The features and make-up of the waste stream are influenced by a number of variables, such as income, level of life, shifts in consumption habits, etc. (Bundhoo, 2018). Understanding the features of the waste stream also critically depends on how garbage is classified. Waste is divided into a number of categories, including ordinary garbage, infectious waste, hazardous waste, and radioactive waste, according to World Bank research carried out in Africa, Liberia. Similar to how garbage is categorized into organic (food scraps, papers, cardboard, and wood) and inorganic (plastics, cans, and bottles) categories, UNEP research discovered that waste is also subdivided into electronic waste categories.(David et al., 2020).

According to Table 1, above, the majority of the trash produced in the majority of Africa is made up of biodegradable organic materials. Considering how much garbage humans produce via their consumption, the majority of waste is biodegradable.

Several wastes are from the kitchen and the home. Thus, an efficient collecting system is required to prevent the spread of illness and other harmful environmental effects. Furthermore, the worldwide tendency for electronic devices, which eventually results in e-waste, is endangering Africa. Thus, an efficient collecting system is required to prevent harm to the environment.

5 Collection and Disposal of Waste in Africa

In Africa, there are three main stages of trash collecting system. The informal phase, primary phase, and secondary phase are those. The phases from household to community collecting locations are essentially the informal and main phases. The secondary phase is managed by institutional entities like urban councils and commercial operators. The typical method of moving waste from community transfer stations to disposal sites is via truck. Waste collection has also used private contractors immediately goes door to door to collect trash from homes. It is typical in East African cities where private garbage collectors have been hired to handle rubbish collection in shopping malls and the area around them. Yet, the local market and hospitals continue to rely on the collection plans put in place by the municipal council, a public parastatal. The "summon to bring" strategy is another collecting method utilized by nations in Africa. With this arrangement, the collection truck already has a set schedule for when days of the week it will arrive and go. It honks its horn when it gets there to signal for people to bring their trash for disposal. The frequency of garbage disposal depends on the socioeconomic classes (levels) of the people: low-income and high-income classes. The wealthy dispose of rubbish more frequently than the less fortunate. Government employees mostly manually load disposable rubbish into trucks, and the amounts of waste collected each time fluctuate. Comparable to other metropolitan councils in underdeveloped nations, the percentage of rubbish collected ranges between 35 and 68% (Bello et al., 2016). Also, the introduction of private-sector operations in the majority of African nations has increased the amount of solid waste collection more than it did when it was completely relied on municipal councils. Figures 1, 2, 3, 4 and 5 show how solid waste is being collected and disposed in Africa (David et al., 2020).

6 Environment and Social Impact of Solid Waste

Significant economic, social, and environmental effects are being brought on by Africa's inadequate trash collection infrastructure, mixed with rubbish disposal that is both unregulated and managed and frequently involves open burning (Abubakar et al., 2022). Waste is leaking into the environment as a result of the continent of Africa's current waste management procedures. Moreover, the careless disposal of garbage in cities increases the danger of sickness, floods, and environmental degradation. Many diseases include an increased risk of cholera, malaria, typhoid fever, dengue fever, and Zika (Nnatu & Obioma, 2018).

Open burning of rubbish produces a substantial amount of air pollution, which has an effect on human health and accelerates climate change. These effects can

Fig. 2 Land fill in the city

Fig. 3 Improper disposal of solid waste

Fig. 4 Daily collection of waste by truck of Monrovia, Liberia

Fig. 5 Illegal waste disposals in urban areas

have wide-ranging effects in addition to local ones. Several African nations, especially those in West and North Africa, have developed into global destinations for end-of-life e-waste and vehicles exported from developed nations in North America, Europe, and Asia. Africa has become a dumping ground for waste, particularly hazardous waste, often from developed countries. Existing recycling methods for electronic garbage, which are sometimes informal, might be hazardous to both persons and the environment. The most vulnerable demographic for this trash is found in Africa, where recycling of waste from electrical and electronic equipment (WEEE) is largely influenced by women and children. A significant source of lead pollution in Africa is the recycling of spent lead-acid batteries in impromptu workshops, which exposes a sizable number of people to plastic makes up 13% of MSW in sub-Saharan Africa, which is more than the global average 13% (Bello et al., 2016) and is more prevalent there. This is compounded by the lack of recycling in Africa. Improper waste management has serious health and environmental consequences. If it persists, it will undermine Africa's efforts to achieve the sustainable development goals (SDGs)(Akurugu, 2018).

7 Solid Waste Management Challenges

Every nation has laws and rules that specify how garbage is to be disposed. The obligations required by law are clearly outlined, particularly in the areas of health, environmental management, and planning. The development of sufficient capacity, not only in terms of money but also in terms of technological and infrastructure developments, is one of the biggest challenges facing waste management in Africa. It is necessary to promote ecologically appropriate waste management that will result in the recovery and recycling of waste streams throughout Africa.

There is a need for access to financial and technical expertise, and this will help waste management towns that are frequently ill-equipped to handle rapid garbage collection and disposal. In addition, some by-laws that assign all waste management tasks to governmental agencies have hindered individuals who have the resources and the desire to enter the waste management industry from doing so. Another impediment is poor governance, lack of transparency, and the presence of corruption in the majority of African nations which are significant issues that hinder effective solid waste management. The importation of inferior goods and ineffective rules and regulations have also aided in the fast rise in waste creation. Additionally, for example Liberia, another significant contributing reason are the functions of the pertinent agencies not being clearly defined and their lack of cooperation is the absence of adequate solid waste (SW) compliance laws. The Public Health Law of 1975, in Liberia, the Environmental Protection and Management Law, the National Environmental and Occupational Health Policy, the National Environmental Action Plan, and other laws, among others, call for a safe, clean, and sanitary environment for all people, but the country's legislation on solid waste management is inconsistent and fragmented. Hence, strong legislation is required to fill the regulatory duties' deficiencies and consistently enforce the management of MSW in accordance with international best practices.

8 Current Statistics of Solid Waste in Some African Cities

Recent solid waste figures from African cities, between 2012 and 2016, the amount of rubbish generated annually in sub-Saharan Africa (SSA) grew from 81 million tons to 174 million tons, with an estimated 269 million tons generated by 2030 (Adedara et al., 2023). The estimated coverage of SSA's municipal solid waste (MSW) collection in 2018 was 44% (Orhorhoro & Oghoghorie, 2019). In SSA, the rates of garbage collection and coverage are 65% and 67%, respectively (Brighton

Kaonga, 2000). Although there is typically a lack of waste characterization data specifically for African cities and nations, what little data are available indicates that the MSW stream in an average African city at the point of disposal contains a high putrescible organic component. About 88,000 kg of garbage was produced daily in Jimma, Ethiopia, with an average generation rate of 0.55 ± 0.17 kg per person per day (Getahun et al., 2012).

Papers, plastics, glassware, non-biodegradable garbage, combustible waste, and other waste kinds are among the solid waste produced in African nations. Solid trash is not always composed of the same materials; biodegradable waste makes up the largest percentage fraction (Adhikari, 2022; Sow, 2019). Over 62.5% of the solid waste created in the countries that make up the East African Community (EAC) is organic, with papers and plastics making up the remaining 19.6%. The amount of waste produced daily per person in developing nations ranging from 0.25 kg to 1.38 kg, and the majority of the components in waste are biodegradable. Improved and effective waste management solutions are required because of the major difficulty of inefficient solid waste management in African nations (Bello et al., 2016).

9 Some Diseases and Their Causing Agents from Solid Waste

Solid waste can contain various disease-causing agents, including pathogens such as bacteria, viruses, and parasites(Krystosik et al., 2020). These pathogens can originate from humans or animals and can be present in the skin, saliva, urine, and feces. Numerous health hazards, such as skin infections, systemic lupus erythematous, and vector-borne diseases, have been linked to solid waste exposure. A substantial risk of infectious and vector-borne diseases might result from improper solid waste management (SWM) methods, such as dumpsites and careless garbage disposal, according to studies (Vinti et al., 2023). Studies have shown that solid waste accumulation can attract disease vectors and reservoirs, such as mosquitoes and rodents, increasing the risk of disease transmission. Additionally, because COVID-19 can persist on surfaces for lengthy periods of time, inadequate waste management may also play a role in the virus's transmission (Megna et al., 2017).

Risks to one's health at work are also connected. Furthermore, it has been discovered that occupational contact to solid waste results in the presence of infectious viruses that can reproduce and cause infection, such as the human adenovirus (HAdV) and the torque teno virus (TTV) (Tshivhase et al., 2022).Vector-borne diseases can spread and proliferate as a result of improper solid waste management. Additionally, because COVID-19 can persist on surfaces for lengthy periods of time, inadequate waste management may also play a role in the virus's transmission. Solid waste management is also linked to dangers to one's health at work, such as respiratory problems, allergies, infectious diseases, and injuries. Appropriate solid waste management procedures, such as closing open dumps and equipping personnel with protective gear, should be put into place to solve these problems(Villa et al., 2022)

Governments and international organizations should offer funding and assistance to enhance waste management systems and protect workers' health and safety.

10 Opportunity in Solid Waste as a Resource

Solid waste has several applications as a resource. Phase change materials (PCMs) can be encapsulated in solid waste products to create form-stable phase change materials (FS-PCMs) (Zhang et al., 2023). Making waste-derived membranes for water treatment applications is another possibility. These membranes can be manufactured from solid waste materials such plastics, biopolymers, and recycled inorganics (Samavati et al., 2023). Furthermore, supplemental cementing materials (SCMs) made from industrial solid waste, such as red mud, can be employed to enhance the mechanical qualities of cement in high-temperature environments. Additionally, solid waste can be used to create metal organic framework (MOF) and magnesium hydroxide (MH) composites, which can be used to flame retard polymer polymers and remove phosphate (Tu et al., 2021).

Through waste-to-energy methods including pyrolysis, gasification, incineration, and hydrothermal carbonization, solid waste can be exploited as a source of energy. Opportunities to create a "secondary resources sector" are still undeveloped in Africa. Africa has a recycling rate of less than 10%, with less than 10% of its countries having recycling facilities that run well and are equipped with the infrastructure needed for effective waste management (Amankwa et al., 2021). Due to current waste management procedures, waste is not taken into account for the potential benefits it might have on regional economies (Sin & Tueen, 2023). Organic material makes up between 60.0% and 80.0% of garbage in Africa, making it a potential source of methane. The loss of fiber and other secondary resources that may be reintroduced into local value chains is a result of Africa's inadequate waste management and recycling infrastructure. There were resources that might have been reintroduced into the local and regional economies to assist production and lessen the financial strain of importing goods. According to initial assessments, diverting trash from landfills and toward reuse, recycling, and recovery might, at a conservative estimate, provide an additional US$8 billion annually to the continent of Africa's economy (Bello et al., 2016). Providing the continent with important socioeconomic potential. Additionally, if it is done appropriately this may minimize the negative effects of current waste disposal practices on the health of people and the environment. If garbage had to be carefully collected and channeled toward reuse, recycling, and recovery, the continent would benefit greatly (Bello et al., 2016).

11 Recommendations

The production of landfill gas for power generation is one promising technological approach for handling solid waste in Africa. This addresses concerns like insufficient power production and greenhouse gas emissions by removing gas from landfills and using it to create electricity. Reusing trash to grow animal feed is another way to solve the problem. This can help the aquaculture sector grow and lessen the need for fish meals. Furthermore, there is hope for sustainable water purification in African nations due to the value-adding of locally sourced waste materials as adsorbents, flocculants, or photocatalysts in wastewater treatment plants. Additionally, the creation of a three-stage anaerobic digestion plant has demonstrated potential in controlling solid waste and generating green energy from biodegradable garbage. These technological advancements present chances to enhance waste.

African leaders should approach the global community for assistance. International communities are renowned for their technological expertise and knowledge; therefore, as a result, African nations may enter into a bilateral investment agreement with them in order to manage waste streams in Africa in an environmentally appropriate manner.

There should be compliance with pertinent international agreements on solid waste and aid to African nations. Additionally, if one has not already been organized, a summit of all African nations should be held. It will act as a forum for the discussion of urgent and contemporary issues related to waste management. Moreover, laws and regulations need to be strengthened, and offenders need to be held accountable.

12 Conclusion

Africa's solid waste management industry has significant obstacles, and there are rising worries about the inadequacies of waste management practices throughout. In delving deeper into the intricacies of solid waste management in Africa, it is essential to recognize that the challenges extend beyond the physical disposal of waste. The issue encompasses a web of socioeconomic, cultural, and environmental factors that necessitate a holistic and context-specific approach.

Africa's rapid urbanization, driven by population growth and economic development, has led to increased waste generation. However, the existing waste disposal infrastructure often struggles to keep pace with this surge, resulting in unregulated dumpsites, open burning, and other unsustainable practices. This not only poses immediate health hazards to communities but also contributes to long-term environmental degradation.

Furthermore, the lack of awareness and education on proper waste management exacerbates the problem. Many communities may not be fully informed about the impacts of improper waste disposal on their health and the environment. Therefore, any effective solution must include robust education and awareness campaigns that empower individuals to make informed choices about waste disposal, fostering a collective commitment to sustainable practices.

Collaboration emerges as a central theme in addressing Africa's solid waste challenge. Governments, local authorities, non-governmental organizations, and international bodies must work together to develop and implement comprehensive waste management strategies. These strategies should incorporate the diverse needs and circumstances of different regions, considering factors such as urbanization levels, cultural practices, and economic resources.

Investment in modern technologies and innovation is pivotal to revolutionizing the solid waste management landscape in Africa. Smart waste collection systems, recycling facilities, and waste-to-energy projects can significantly contribute to reducing the environmental impact of waste while creating economic opportunities. Governments and private enterprises should explore partnerships to facilitate the adoption of these technologies, ensuring that they align with the specific needs and capacities of local communities.

Embracing the concept of a circular economy is another crucial aspect of a sustainable solid waste management framework. This involves minimizing waste generation through product design, encouraging recycling, and promoting the reuse of materials. By shifting the focus from a linear "take, make, dispose" model to a circular one, Africa can harness the economic and environmental benefits of resource efficiency. Finally, addressing the solid waste crisis in Africa demands a nuanced and collaborative approach that goes beyond mere infrastructure development. It necessitates a transformation in mindset, from viewing waste as a problem to recognizing it as a potential resource. By integrating education, technology, and inclusive policies, Africa has the opportunity not only to mitigate the immediate challenges of waste management but also to pave the way for sustainable development that respects both the people and the planet. Only through concerted efforts and shared responsibility can turn Africa's solid waste challenge into a catalyst for positive change and resilience in the face of a rapidly evolving world.

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Assessment of Ozone Pollution in the Foothills of the Central Himalayan Valley

Kiran Sharma, S. Harithasree, Imran Girach,
Lokesh K. Sahu, Narendra Singh, S. Suresh Babu,
and Narendra Ojha

1 Introduction

Surface ozone is a major air pollutant that causes harmful effects on human health and the environment (Monks et al., 2015). Ozone is also a strong oxidant and plays an important role in tropospheric chemistry (Atkinson, 2007). It is a secondary pollutant that is formed by the photochemical reaction of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx). Substantial ozone production occurs in polluted environments such as the Indo-Gangetic Plains (IGP); however, ozone can also be readily transported to relatively cleaner, remote environments such as the Himalayan regions. Besides the inflow of polluted air, the Himalayan valley region is also undergoing rapid urbanization (https://cpcb.nic.in/Actionplan/Dehradun.pdf). However, surface ozone measurements have remained mostly limited to the IGP and other big cities. In view of this

K. Sharma (✉)
Graphic Era (Deemed to be University), Dehradun, India
e-mail: kiransharma@geu.ac.in

S. Harithasree
Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad, India

Indian Institute of Technology, Gandhinagar, Gujarat, India

I. Girach
Space Applications Centre, Indian Space Research Organisation, Ahmedabad, India

L. K. Sahu · N. Ojha
Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad, India

N. Singh
Aryabhatta Research Institute of Observational Sciences, Nainital, India

S. S. Babu
Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, India

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scenario, in situ ozone measurements were initiated in April 2018 at Graphic Era University, which is representative of the Doon Valley in the foothills of the Himalayas. These ozone measurements have been combined with satellite data and model results to study the impacts on human health and investigate the ozone formation regime in this region.

2 Experimental Details and Datasets

Surface O_3 measurements were conducted using an online ultraviolet (UV) photometric analyzer (Environnement S.A., France model O_3 42) placed ~17 m above the ground to minimize any potential local influences. The O_3 concentration in the air samples was measured utilizing the absorption of UV light by O_3 molecules based on the Beer-Lambert law. Further details of the analyzer can be found in Ojha et al. (2019). The hourly O_3 mixing ratios for the period April 2018—October 2023, excluding several months in 2020, were used for the analysis. Observations could not be conducted during several months of 2020 due to COVID-19. Tropospheric columns of NO_2 and HCHO are obtained from the Tropospheric Monitoring Instrument (TROPOMI) aboard the Sentinel-5 Precursor satellite (Veefkind et al., 2012). TROPOMI is an imaging spectrometer that derives columnar densities of trace gases at a spatial resolution of 5.5 km × 3.5 km based on their absorption properties at UV and optical wavelengths. The time series of these data for the study region (averaged ±25 km around the site) were obtained after filtering values when the cloud fraction >30%. In addition, 3-hourly reanalysis data of surface ozone from the Copernicus Atmosphere Monitoring Service (CAMS) (Inness et al., 2019), which is available at 0.75° × 0.75° spatial resolution, were analyzed.

3 Results and Discussions

Figure 1 shows the mean diurnal and seasonal variability in ozone over Dehradun during the study period. The diurnal variation in surface ozone over the study location shows a buildup of ozone during the noon hours and decay during the night hours. The annual mean diurnal pattern shown in Fig. 1a exhibits a daytime (11:00–17:00) high of ~33.8 ± 3.4 ppbv and a nighttime (00:00–06:00) low of ~11.6 ± 0.7 ppbv. This noontime buildup was attributed to intense photochemistry involving precursors from local pollution, whereas the nighttime low was due to chemical titration (Seinfeld & Pandis, 2016). The monthly variation in noontime surface ozone in Fig. 1b shows a maximum during the premonsoon months with a prominent peak of 63.8 ± 15.3 ppbv in May, and a small enhancement during the postmonsoon months, peaking at 35.6 ± 9.0 ppbv in October. The intense buildup of surface ozone during the premonsoon season was a manifestation of intense local photochemistry and the transport of precursors from regional-scale biomass burning emissions in the IGP (Ojha et al., 2012; Roy et al., 2022).

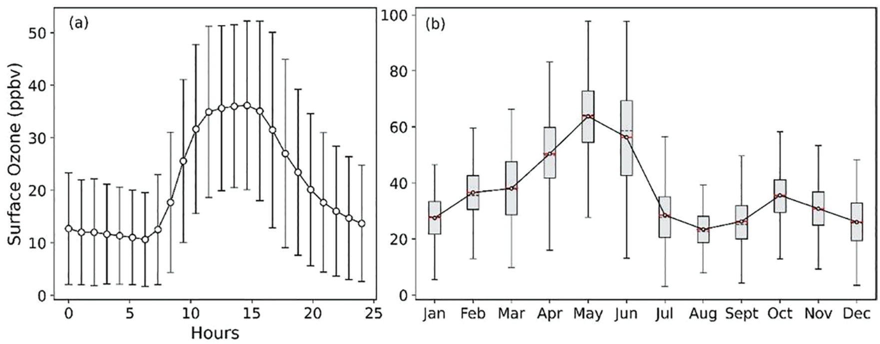


Fig. 1 (**a**) Annual mean diurnal variation in surface ozone, (**b**) mean seasonal variation in noontime (11:30—14:30) surface ozone for the period April 2018—October 2023. The upper and lower whiskers extend 1.5 × the interquartile range (IQR) from the 25th and 75th percentiles represented by the box edges. The horizontal solid and dotted lines within each box represent the monthly mean and the median, respectively

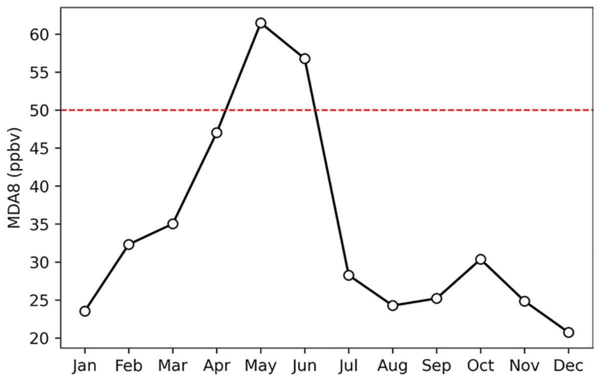


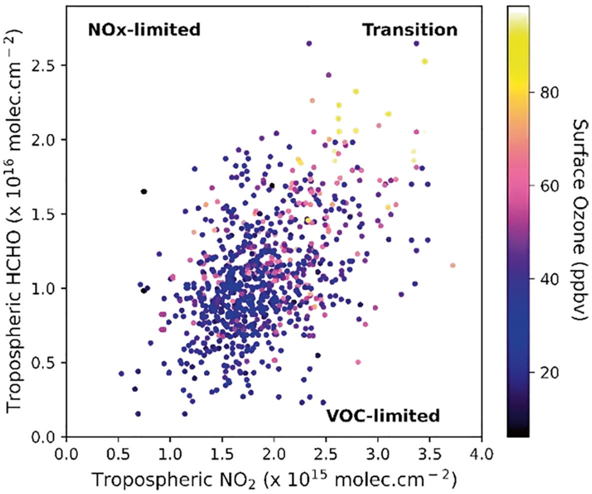
Fig. 2 Variation of monthly mean MDA8 values derived from the in situ measurements during April 2018–October 2023. The red dotted line shows the critical limit of MDA8 (50 ppbv). For a detailed description and analysis, readers may refer to Harithasree et al., 2024

To assess the impacts of ozone exposure on human health, the MDA8 index was calculated. The impact of ozone exposure beyond the critical limit of 50 ppbv is considered detrimental to human health. However, the monthly mean MDA8 ozone concentration in Fig. 2 is seen to exceed the critical limit during the months of May and June. During April, the mean MDA8 ozone is just below the critical limit at ~47 ppbv, indicating stronger health impacts during these months (World Health Organization, 2000; World Health Organization, 2021). The ozone levels exceeded the MDA8 threshold at 165 days (~13% out of 1296 days), of which 147 (98%) days were from April to June. The ozone levels were in excess of about 60% (147 of the total 247 days in April—June) of the days during April—June.

In order to design control strategies for the mitigation of ozone pollution, ozone chemistry over the local environment must be quantitatively understood. Based on the NOx levels, the ozone formation regime could be one of three regimes: VOC-limited, NOx-limited, or transition (Sillman, 1999) (Figs. 3 and 4).

As suggested by Martin et al. (2004), TROPOMI-retrieved tropospheric HCHO and NO_2 colocated with ozone measurements were used to investigate the

Fig. 3 Correlation between TROPOMI-retrieved tropospheric HCHO versus NO_2, color-coded with the observed surface O_3. The O_3 values less than 5 ppbv have not be considered



O_3-VOC-NOx sensitivity over the environment. The thresholds obtained for the chemical regime calculated following Ren et al. (2022) are 5.65 and 10.38 (Harithasree et al., 2024). These results suggested that ozone levels between 5.65 and 10.38 are in the transition regime and that values less (more) than 5.65 (10.38) lie in the VOC-limited (NOx-limited) regime. This implied that ozone production in the Doon Valley was either in transition or VOC-limited regimes. Therefore, a reduction in the emissions of both NOx and VOCs is required to control ozone pollution in the region.

Ozone observations were also used to assess the performance of a global model (CAMS reanalysis) over the complex Himalayan region. A comparison of the noontime ozone observations and CAMS simulation showed that the model was able to reproduce ~80—90% of the temporal variabilities in the noontime values over different seasons. However, we noticed limited ability of the model in capturing nighttime ozone variations, which is attributed to insufficient spatial resolution in resolving the Himalayan terrain.

4 Conclusions

In situ surface O_3 measurements were conducted over the Doon Valley of the Himalayas, and the data were analyzed in conjunction with satellite measurements and model results. The variability of surface O_3, its impacts on human health, and the photochemical regime over the environment have been investigated. The seasonal variability in surface O_3 showed high values during the premonsoon months (~64 ppbv; May) and a small enhancement in the postmonsoon months. Global model (CAMS reanalysis) was able to reproduce the day-to-day variability in noontime ozone during different seasons. The MDA8 O_3 exceeded the critical limit of 60% of the days in the months of April—June, suggesting a significant risk of health impacts during this period. The O_3 photochemical regime was seen to be transition

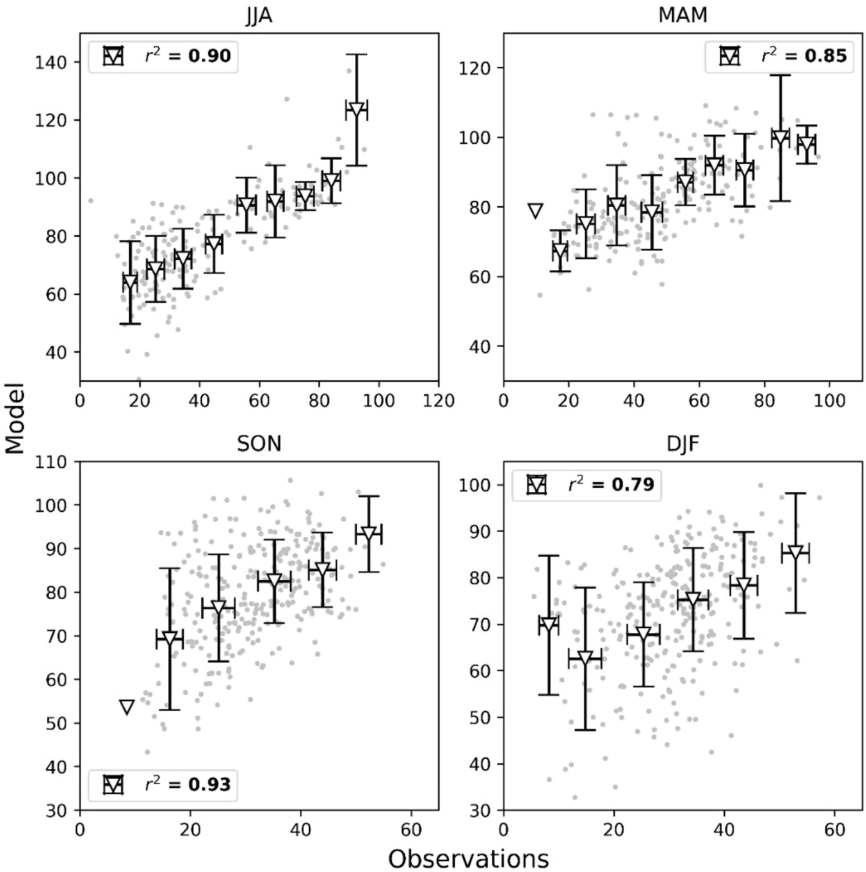


Fig. 4 Scatterplots observed against CAMS-simulated ozone levels during April 2018–June 2022. The significant correlations ($p < 0.05$) are shown in bold

or VOC-limited. Hence, a reduction in both VOCs and NOx was required to reduce ozone pollution over this rapidly urbanizing region in the Himalayan foothills.

Author Contributions Kiran Sharma carried out the measurements with support from S. Suresh Babu. S. Harithasree, Imran Girach, and N. Ojha analyzed observational, satellite, and model datasets, respectively. N. Singh and L. K. Sahu helped with the analysis and contributed to the interpretations.

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Part IV

Sustainable Development Goals and Policies, Ecological Impact and Conservation, Water Resources and Agriculture

Perceptions of Climate Change and Its Impacts on Local Communities Along the Noakhali Coast in Bangladesh

Edris Alam, Md Imtiaz Uddin, Paul Donald Johnstone, Morshed Hossan Molla, Mohammad Mohaiminul Islam, Sumon Miah, Tanvir Mahtab Nasim, Md Azizul Hoque, and Nadia Afrin

1 Introduction

Being a low-lying delta, Bangladesh stands out as one of the worst nations to the negative consequences of climate change and associated outcomes globally (Alam et al., 2018; Chowdhury et al., 2022). The nation has been ravaged by severe climatic occurrences, such as rising sea levels, tropical cyclones, river floods, land erosion, and the intrusion of salinity into soil and water (Alam et al., 2023; Alam & Mallick, 2022). These climate extreme events resulted in the loss of lives and the cause of injuries, damage to critical infrastructure including roads, bridge, and houses. This adversely affected the livelihood and means of people especially the poor who are mostly dependent upon climate-sensitive farming activities (Islam

E. Alam (✉)
Faculty of Resilience, Rabdan Academy, Abu Dhabi, United Arab Emirates

Department of Geography and Environmental Studies, University of Chittagong, Chittagong, Bangladesh
e-mail: ealam@ra.ac.ae

M. I. Uddin
Department of Spatial Information & Modelling, Leibniz Institute of Ecological Urban and Regional Development, Dresden, Germany

P. D. Johnstone
Faculty of Resilience, Rabdan Academy, Abu Dhabi, United Arab Emirates

M. H. Molla
Young Power in Social Action (YPSA), Chittagong, Bangladesh

M. M. Islam · T. M. Nasim · M. A. Hoque · N. Afrin
Disaster and Development Organization (DADO), Chittagong, Bangladesh

S. Miah
Department of Meteorology, University of Dhaka, Dhaka, Bangladesh

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et al., 2022). This study has investigated climate change perceptions and reported impacts along the Noakhali coast in Bangladesh.

1.1 Experiencing Climate Change: Impact on Coastal Communities

Coastal areas are one of the most affected and vulnerable locations for the detrimental impacts of climate change (Becker et al., 2023). These effects range from ecosystem, biodiversity, and water resources to the livelihood of coastal communities (Barnes et al., 2020; Fragkopoulou et al., 2023). For example, fishers live in uncertainty as they cannot predict the weather, bigger sea waves, and peak season events because of climate change (Alam et al., 2021). Bangladesh is positioned at seventh place as a nation significantly affected by climate change (Eckstein et al., 2021). These changes also have a negative impact on agriculture, health, livelihood of coastal communities (Ali & Hossen, 2022). Extreme cyclone events such as Sidr and Aila changed the living pattern of local inhabitants as the fishing and agricultural lands were reduced (Kabir et al., 2016). In the aftermath of Cyclone Sidr, individuals experienced various health issues and ailments, including diarrhea, dysentery, viral fevers, respiratory problems such as coughs and colds, skin conditions, and chickenpox. (Kabir et al., 2016). In the scope of this research, our primary aim was to evaluate the community's awareness and the detrimental impacts of climate change in the susceptible central coast of Bangladesh.

1.2 Climate Change Vulnerability and Adaptation

Vulnerability is the degree of incapability of one's group to cope with the detrimental impacts of climate change (IPCC, 2022). Human societies are vulnerable to variations in the climate as their livelihood largely is dependent upon its predictability and frequency. Vulnerability can be categorized into three broad categories: firstly, in terms of exposure to hazardous events and their relation to people and structures; secondly, in terms of human relationships; and lastly, in a combination of the physical event and underlying causal characteristics (Dolan & Walker, 2006). Humans adapt to change by different coping strategies and it is essential to reduce vulnerability in order to survive or prosper (Adger et al., 2003). The GoB is proactively implementing policies, strategies, and action plans to tackle the detrimental impacts of climate change. Adaptation can be approached from multiple angles, taking into account aspects such as scale, actors, influencers, procedures, and sectors, as outlined by Castells-Quintana et al. (2018) and Schipper (2020). It can also manifest in two primary forms: incremental and transformational. Incremental adaptation entails actions focused on preserving the core essence and integrity of a system or process at a particular level of magnitude. On the other hand, transformational adaptation entails implementing fundamental changes to address the detrimental impacts of climate change. These transformative changes can manifest in various ways, such as technological or biological system innovations, shifts in financial structures, or modifications in rules and governance frameworks. A concrete instance of transformational adaptation involves the creation of guidelines for screening climate risks, which have the potential to enhance the resilience of downstream development projects against climate-related risks.

Smit and Wandel (2006) broadly classified adaptation from two perspectives: government-led initiatives aimed at safeguarding society and the autonomous adaptation efforts of individuals. Adaptation assessment involves the process of identifying and evaluating options to address climate change, taking into account factors including accessibility, advantages, expenses, efficacy, productivity, and viability.

1.3 Aim and Objectives

The study's aim was to comprehensively examine the local perceptions of climate change, its symptoms, and documented impacts, while also assessing its effects on gender roles concerning life and livelihood protection along the Noakhali coast in Bangladesh.

2 Materials and Methods

This study effectively tackles various scientific and technical issues associated with the multifaceted realms of climate change and their consequences within coastal communities in Bangladesh. In pursuit of our outlined objectives, a comprehensive research approach was adopted, encompassing a blend of quantitative and qualitative methodologies to gain deeper insights into the way communities perceive climate change and its resulting effects. It is worth noting that both qualitative and quantitative approaches have their inherent limitations, as highlighted by Gregory (2009). However, employing a mixed methods approach, as advocated by Creswell (2009), offers a more robust means of obtaining results compared to relying solely on either qualitative or quantitative methodologies in isolation. In the context of this research, data were meticulously gathered through on-site field visits and surveys. A comprehensive range of data, covering quantitative and qualitative aspects, was collected using closed, semi-structured, and open-ended questionnaires, direct observations (both overt and covert), and in-depth focus group discussions (FGDs).

2.1 Physical Setting of the Study Sites

Noakhali is one of Bangladesh's 64 districts, covering an extensive area of 4202 km^2. This district is emblematic of a vast, flat, coastal, and deltaic terrain situated within the tidal floodplain of the Meghna River delta. It is distinguished by its flat topography and minimal elevation changes. The region experiences diurnal tidal cycles, with fluctuations in tidal activity varying seasonally, most notably during the monsoon season. Encompassing Noakhali on three sides is an alluvial plain, subject to annual inundation and enriched by the deposition of fertile silt carried by the Meghna estuary. The swift currents originating in the Himalayas transport this nutrient-rich silt, and upon reaching the Bay of Bengal, it settles along the coastline, gradually giving rise to new land formations known as *chars*. The geography of this area, characterized by its funnel-shaped location along the Bay of Bengal, renders it vulnerable to a range of natural disasters and climate-related events. The study area encompasses Caring Char and Char Majid within the Noakhali District, spanning the Hatiya Upazila and Subarnachar Upazila, respectively (Fig. 1).

2.1.1 Weather and Climate

Noakhali experiences a tropical climate characterized by abundant rainfall throughout most months, interrupted by a brief dry season. The average annual temperature in Noakhali hovers at 25.6 °C, while the region receives an annual average rainfall of approximately 3302 mm. The month of May stands out as the warmest month of the year, with a mean temperature of 33.6 °C, marking the height of the region's heat. Conversely, January typically marks the coldest period, with an average temperature of 19.5 °C, marking the peak of the cooler season. In terms of precipitation, the driest month in Noakhali is January, with a mere 8 mm of rainfall. On the other end of the spectrum, July experiences the highest levels of rainfall, with an average of 671 mm, signifying the peak of the monsoon season in the region.

2.1.2 Morphology

The geographical landscape of this region is highly dynamic, marked by continuous land accretion surpassing erosion. Many islands in this area are notably vulnerable to the destructive forces of cyclonic storm surges and erosion. What is noteworthy is that the rate of new land formation exceeds that of land erosion in this locale. However, these newly accreted lands initially remain low-lying and susceptible, rendering them unsuitable for human habitation and agricultural use. Despite these inherent challenges, the growing population's land demands drive people toward settlement on these recently formed landmasses.

Erosion is particularly severe along all sides of the region except the northern part. Furthermore, certain mainland areas on the eastern bank of the Meghna estuary, such as Ramgati and Carring Char, are experiencing erosion due to the shifting of tidal channels, which erode and bypass the embankments on the left bank of the Meghna, as well as on both the right and left banks of the Feni River. Aside from erosion, specific regions contend with extended periods of waterlogging caused by encroachments and land reclamation, stemming from the closure of tidal channels. Furthermore, river floods present substantial risks to certain mainland areas bordering the Meghna estuary, especially in the districts of Chandpur, Lakshmipur, Noakhali, and Feni.

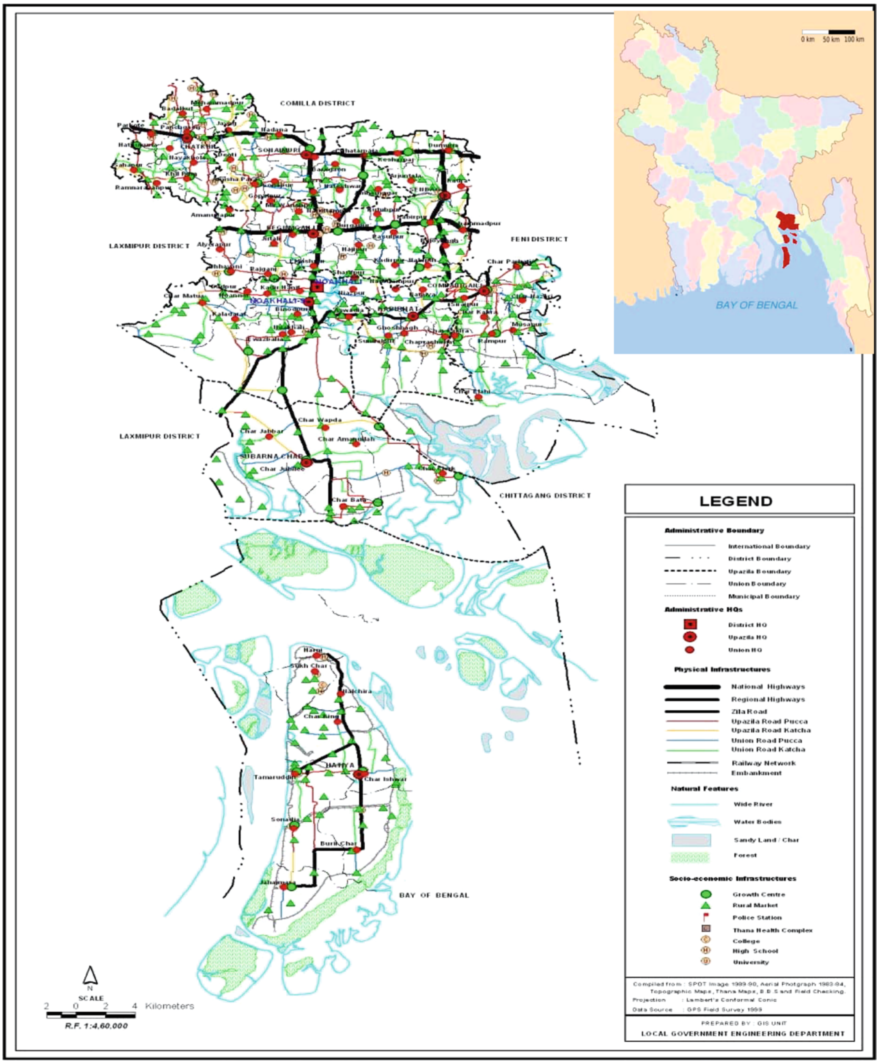

Fig. 1 Location of Noakhali district in Bangladesh

2.2 Data Collection and Analysis

The use of a questionnaire survey helps to obtain specific information on the study of the population impacted by climate change. Apart from collecting secondary information from different government and nongovernment organizations in Bangladesh, the questionnaire survey was conducted with 177 coastal communities who are over 20 years of age. The duration of each interview was 30 min. A group of 37 postgraduate students were trained for data collection. The questionnaire was composed of three parts: (1) socio economic attributes of the participants collected through a structured questionnaire; (2) climate change perceptions and symptoms collected through partially structured and open question; (3) effects of climate change on communities through open-ended question. The field data were collected between November and December 2019.

A focus group discussion (FGD) is a method to convene individuals with similar backgrounds or experiences to discuss a particular topic of relevance. Five focus group discussions (FGDs) were completed during the field survey with a view to collect community-based knowledge on climate change perceptions, symptoms, and impacts. The impact of climate change on embankment and water logging and health were collected through FGDs. Approximately 7–8 persons attended each FGD. The groups comprise with the combination of men and women whose occupation is either farmer or housewife. During each FGD, one team member was tasked with documenting information, issues, and participant responses throughout the session. Particularly relevant and noteworthy comments pertaining to any of the discussed issues were given priority.

To enrich the contents of the research work, secondary data have been collected from the Noakhali District office, CDSP-IV office, Subarnachar Upazila office, CPP Noakhali office of the study area, newspaper reports, research cells, institution, magazines, publications, and especially via Internet sources. The collected information has meshed with raw data collected from the field to furnish the research report.

Upon the comprehensive gathering of data from various sources, a systematic processing and analysis phase is followed. This involved a combination of manual and automated techniques, employing software tools such as MS Excel, and SPSS. The analytical procedure involved statistical techniques, comprising descriptive analysis and the computation of a 5-year rolling mean for temperature and rainfall data. These datasets were then compared with household perceptions of climate change indicators. To offer a deeper insight, frequencies and percentages of answers were computed for questions concerning perceptions, climate change impacts, and adaptation strategies. Various graphical tools such as charts, maps, and photographs were utilized to illustrate the findings of the study.

3 Results

3.1 Social and Demographic Attributes of the Participants

The average age of the participants in this study was 47 years. Approximately, 36.16% of respondent's ages ranged from 30 to 40 years which was the highest percentage among the participants. The percentage of people from 40–50 years was approximately 31.08%, which was the second highest percentage of the respondent's age. A detailed breakdown of participants' ages is presented in Fig. 2. The rest of the people surveyed were from other age groups. The percentage of male and female participants was 61% and 39%, respectively.

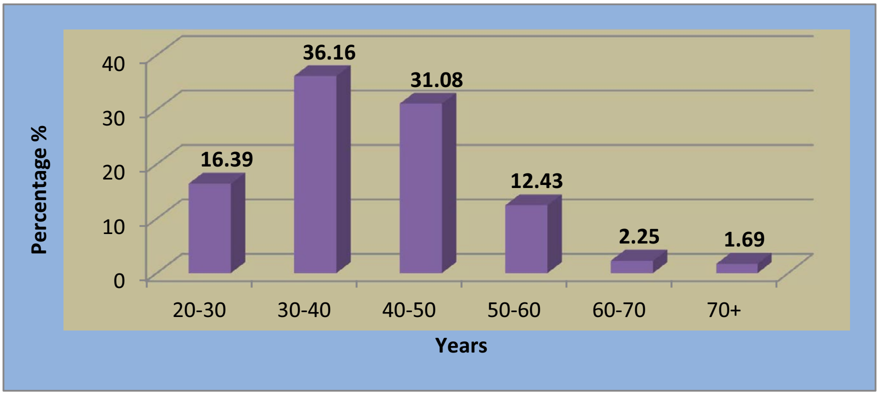

Fig. 2 Age of the participants (Source: Field survey, 2019)

The respondents were mostly illiterate comprising 85% who did not have any formal education. Approximately, 14% had completed below 10 years of schooling. Only 1% of students found to complete above 10 years of schooling. This indicates that those who reside in extremely disaster-prone areas are mostly uneducated and are compelled to live in such places due to alternative skills for livelihood. Among the participants, 46% were farmers, mostly male respondents and 37% were housewives, female respondents. About 9% were engaged in a variety of trading activities. The remaining 8% were students, services, and daily workers.

Data suggest that 87% of houses are Kutcha (made of earthen). Typically, a kutcha house is constructed from mud, bamboo, wood, and straws (Fig. 3). These types of houses are very vulnerable during disaster events. Semi-pucca (built-in) houses were eight. We did not find any completely built-in house in the area. The remaining 5% of houses are made of a variety of non-permanent structures like tent type of houses.

3.2 Perceptions of Climate Change

Assessing people's perception levels serves as a crucial tool for studying the detrimental impacts of climate change and developing strategies to deal with and address climatic disturbances. Hence, it is imperative to gain a comprehensive understanding of various climatic events. Respondents were queried about their own perceptions and awareness regarding climate change. The selected community experiences various climatic shifts that significantly affect their overall livelihood patterns. Based on their perceptions and awareness, they adapt their livelihood strategies to accommodate these climate-induced changes. To capture respondents' attitudes toward climate change, we distinguished between climate and weather using appropriate local terms in the Bengali language. Additionally, we collected climatic information from respondents at different levels, initially explaining concepts in the local

Fig. 3 Housing condition of the study population (Source: Field survey, 2019)

language. In response to inquiries about their understanding of the term "climate change" within the study areas, 80% of respondents lacked awareness. However, those who could articulate climate change in their language described it as an increase in cyclones, floods, temperature, salinity, and noticeable alterations in seasonal patterns.

3.3 Symptoms of Climate Change

When explaining the meaning of climate change, the participants perceived a variety of symptoms of climate change including extreme temperature, rainfall, and drought (Table 1). A total of 14.12% of people believe the amount of rainfall has been changed due to climate change, whereas 13.56% of people observed changes in temperature. According to 9.04% respondents of the study, the number of days without rain was increasing (long summer season). The same percentage of people also believe late winter was the result of climate change. In addition, 8.47% people of the study areas believe that extremely hot summer was the result of climate change. Moreover, the same percentage of people (7.91%) thought that the intensity and number of cyclones were increasing because of climate change.

Table 1 Observed symptoms of climate change

Symptoms	Frequency	Percentage (%)
Temperature	25	13.56
Rainfall	25	14.124
Long summer season	16	9.04
Extreme hot summer	15	8.47
Heat wave	3	1.7
Early monsoon	5	2.2
Late monsoon	9	5.08
Longer monsoon	3	1.70
Short monsoon	3	1.70
Cold wave	3	1.70
Early winter	4	2.26
Late winter	16	9.04
Long winter	5	2.82
Changes in timing of rainfall	18	10.17
Intensity of cyclone	14	7.91
Increase in number of cyclone	14	7.91
Total	**177**	**100**

Source: Field survey, 2019

3.4 Effects of Climate Change

The participants of this questionnaire faced a variety of the detrimental impacts of climate change in the central coast of Bangladesh. These include an increase in river floods, tropical cyclones and storm surges, coastal erosion, seasonal variation, sea level rises, salinity intrusion, and excessive rainfall in a short duration (Table 2).

3.4.1 Tropical Cyclones, Floods, River Bank Erosion, and Sea Level Rise

Like many other areas, the Bangladesh coast is susceptible to a range of multi-hazard threats, including cyclones and storm surges. Approximately, 11.3% inhabitants of climate change-affected areas opines that changing climate condition is the reason behind the high increase of cyclone. On the other hand, 33.9% of people consider that cyclone has moderately increased from climate change effects. A total of 47.45% of respondents think that climate change plays a key role for the increase of cyclone. Around 47% of participants of the study think that climate changes impact is responsible for a moderate increase in the storm surge. On the contrary, 19.75% of people think the storm surge has decreased.

From the study, it was revealed that 21.47% of people believe that climate change is the main reason for highly increased flood occurrence. Furthermore, 44.06% of people mentioned that climate change effects have increased the occurrences of flood. Another 33.9% respondents of suggested that flood occurrences have moderately increased resulting from climate change effects. The low-lying coastal zone in the study area sits between the Meghna River system on one side and cyclone and

Table 2 Changes due to climate change

Patterns	Level (In Percent) (frequency in bracket)					
	L1	L2	L3	L4	L5	Total
Occurrence of flood	21.47 (38)	44.06 (78)	22.6 (40)	11.87 (21)	0 (0)	100 (177)
Increase of cyclone	11.3 (20)	47.45 (84)	33.9 (60)	7.35 (13)	0 (0)	100 (177)
Riverbank/coastal erosion	11.3 (20)	13 (23)	41.8 (74)	19.78 (35)	14.12 (25)	100 (177)
Seasonal variations	11.87 (21)	19.78 (35)	41.24 (73)	18.64 (33)	8.47 (15)	100 (177)
Storm surge increase	6.22 (11)	20.91 (37)	46.9 (83)	19.75 (35)	6.22 (11)	100 (177)
Salinity intrusion	9.02 (16)	43.51 (77)	28.25 (50)	13(23)	6.22 (11)	100 (177)
Sea level increase	14.69 (26)	38.99 (69)	21.47 (38)	16.95 (30)	7.9 (14)	100 (177)
Excessive rainfall	14.69 (26)	38.99 (69)	21.47 (38)	16.95 (30)	7.9 (14)	100 (177)

Levels: 1 = Highly Increase, 2 = Increase, 3 = Moderately Increase, 4 = Decrease, 5 = Highly Decrease (Source: Field survey, 2019)

associated storm surges from the Bay of Bengal on the other. This situation was exacerbated by climate change. Floods lead to social disruptions and contribute to a scarcity of potable water, as surface water becomes polluted with organic and inorganic matter.

Satellite image analysis reveals that Bangladesh's coastal area has expanded by approximately 20 square kilometers annually over the past few years. This growth can be attributed to both the Coastal Embankment Project (CEP6) dams constructed in the 1950s and 1960s, as well as natural sedimentation processes, resulting in the creation of hundreds of square miles of new land. However, this land accretion not only generates new land but also leads to the silting up of river beds, which contributes to prolonged and severe flooding, prompting mass migration. Almost every year, people are forced to vacate their lands, leading to the loss of livelihoods and property due to river erosion (Fig. 4). The impacts of river erosion are enduring, often taking several decades for families to recover from the losses incurred. Despite these challenges, there has been limited progress in improving the lives of those affected by erosion, largely due to resource constraints. The study finds that 11.3% of people believe that climate change has an effect toward the high increase of riverbank erosion. A group of people (41.8%) opines that climate change is the cause for a moderate increase of the riverbank erosion in their area.

The coastal regions of Bangladesh are currently grappling with salinity issues, a problem expected to worsen due to climate change. A study by the Government of Bangladesh (GoB) suggests that the salinity levels in the soil have risen from approximately 8330 square kilometers in 1973–10,560 square kilometers in 2009. Among these areas, approximately 4530 square kilometers are affected by elevated

Fig. 4 Unprotected coastal boundary land (Source: Field survey, 2019)

salinity levels. The salinization of river water is anticipated to lead to disruptions, including paucity of drinking water, limited water availability for irrigation during rain-fed agriculture, and notable alterations in marine ecosystems. Changes in river salinity and freshwater availability may also impact fish habitats and the productivity of freshwater fisheries.

Bangladesh is extremely susceptible to the rise in sea levels, resulting from climate change. According to the World Bank (2000), an increase in sea levels of 10 cm, 25 cm, and 1 m by 2020, 2050, and 2100, respectively, would affect 2%, 4%, and 17.5% of the entire land area. Observed sea level rise between 1948 and 2004 is currently believed to be approximately 2 mm along the Bangladesh coast (Alam et al., 2018). A total of 14.69% people of the study area observed a high increase in sea level whereas 38.99% of residents view it as an increased level. Interestingly, one-fourth opined about the decreases in sea level.

Excessive rainfall is observed in the study areas by 75.15% of respondents. Among this, 14.69% of people said that excessive rainfall has highly increased due to climate change. On the other hand, 21.47% of respondents denote the changes as moderately increased. An additional 38.99% of people denote it as increased which occupy the highest proportion.

3.5 Anthropogenic Contribution to Climate Change

Respondents were asked if they believe that there was an anthropogenic contribution to climate change. The participants have mentioned a variety of anthropogenic factors including emission of greenhouse gases, fossil fuel burning, manufacturing industries, deforestation, and agriculture activities (Table 3).

3.6 Losses Resulted from Climate Change Effects

Climate has an enormous negative impact on various sectors related to human and environment. Respondents of the study were asked about the losses resulting from climate change effects. They also ranked the losses in terms of increasing level. Losses associated with climate change effects have been discussed in this section in light of peoples' experience explored from the study.

3.6.1 Losses on Agriculture

Climate has an enormous negative impact on agricultural outcomes in Bangladesh. Given that agriculture serves as the primary livelihood for the local communities, participants were deeply engaged during surveys and discussions regarding the challenges and risk factors associated with agricultural activities (Table 4).

Climate change impacts seasonal crop production, leading to increased prevalence of crop diseases and alterations in rainfall patterns and temperatures. These changes result in soil infertility and hinder crop production. The participants identified three causes of a decrease in crop production: increase crop disease, pests, and loss of nutrients and soil fertility. The participants highlighted an increase in crop diseases leading to reduced agricultural production, attributed to the detrimental impacts of climate change. The changes in rainfall pattern and temperatures resulted in changes to the emergence of insect pests of crops. They also identified losses of nutrients and soil fertility are responsible for the decline of agricultural production.

3.6.2 Decrease in Fish Production

Decrease in fish production was the most commonly mentioned loss of climate change effects which has been mentioned as highly increased by 15% of respondents, in addition to this, 21.47% of people identify it as an increase. On the other hand, 12.99% of respondents express it as a moderate increase. It is worth noting that during the FGDs, participants highlighted the loss of freshwater species. This loss has imposed additional costs on people's livelihoods to some extent.

Table 3 Anthropogenic Contributor to Climate Change

	Level (In Numbers)				
Anthropogenic factors	L-1	L-2	L-3	L-4	L-5
Emission of greenhouse gas	0	1	5	1	7
Burning of fossil fuel	3	8	5	2	5
Manufacturing industries	1	9	16	8	1
Deforestation	20	27	31	9	16
Agriculture	11	41	27	20	11
Others	0	2	0	1	2
Don't know	1	0	0	1	0

Levels: 1 = Highly Increase, 2 = Increase, 3 = Moderately Increase, 4 = Decrease, 5 = Highly Decrease (Source: Field survey, 2019)

Table 4 Agricultural losses and problems associated with climate change

Types of Elements	Level (In Percent) L-1 (f)	L-2 (f)	L-3 (f)	L-4 (f)	L-5 (f)	N/A (f)	Total % (F)
Shortage of food	28.25 (50)	41.8 (74)	12.99 (23)	3.39 (6)	6.78 (12)	6.79 (12)	100 (177)
Effects on infrastructure	17.51 (31)	44.63 (79)	12.99 (23)	6.21 (11)	7.34 (13)	11.32 (20)	100 (177)
Shortage of drinking water	18.65 (33)	20.34 (36)	20.90 (37)	4.52 (8)	5.65 (10)	29.94 (53)	100 (177)
Increase of infectious disease epidemics	13.86 (25)	19.87 (35)	16.46 (29)	4.52 (8)	1.69 (2)	43.60 (77)	100 (177)
Mixing of saline water with ground water	14.05 (25)	16.95 (30)	16.95 (30)	16.95 (30)	12.42 (22)	22.68 (40)	100 (177)
Lack of jobs/ increase seasonal labor	16.95 (30)	20.34 (36)	12.43 (22)	7.91 (14)	14.12 (25)	28.25 (50)	100 (177)
Occupational change	13 (23)	29.95 (53)	14.69 (26)	5.08 (9)	8.47 (15)	28.81 (51)	100 (177)
Price hike	22.60 (40)	21.47 (38)	13 (23)	4.52(8)	7.91 (14)	30.50 (54)	100 (177)

Levels: 1 = Highly Increase, 2 = Increase, 3 = Moderately Increase, 4 = Decrease, 5 = Highly Decrease (Source: Field survey, 2019)

3.6.3 Losses on Biodiversity

The participants mentioned extinction of plants and species in the study area. Salinity intrusion, deforestation, poaching, sudden environmental disturbances, extreme heat, and ecosystem degradation (Table 5). Crops and vegetation species loss were mentioned to some extent. It has been mentioned as having increased by 11.22% with respondents, identifying a 16.95% increase. On the other hand, 19.77% of respondents express it as a moderate increase. This result coincides with FGDs that also reported loss of crops and vegetation species. As mentioned in previous sections, the heightened vulnerability to natural disasters resulting from climate change would significantly impact the animal husbandry industry (Cheng et al., 2022). The study finds that 40% of participants acknowledged the losses of animal species due to climate change effects. Here, an important cause for animal species losses has been given which has been explored in the study.

3.6.4 Decrease in Forestland and Shortage of Cattle Food

While the livelihoods of coastal communities are susceptible to the detrimental impacts of climate change, many are striving to meet their basic needs through cattle rearing. However, they are increasingly finding it challenging to afford fodder and feed for their livestock. A total of 40% of the total respondents believe that the shortage of cattle food is associated with the losses of animal species, resulting from climate change effects. Forest ecosystems are pivotal in the global biogeochemical cycle and wield substantial influence on the Earth's climate. The boundaries of

Table 5 Biodiversity losses and problems associated with climate change

	Level (In Percent)						Total
Types of Elements	L-1 (f)	L-2 (f)	L-3 (f)	L-4 (f)	L-5 (f)	N/A (f)	% (F)
Crops/vegetation species	11.22 (20)	16.95 (30)	19.77 (35)	16.95 (30)	19.77 (35)	15.25 (27)	100 (177)
Decrease of forestland	8.47 (15)	25.42(45)	16.95(30)	16.95 (30)	16.95 (30)	15.26 (27)	100 (177)
Shortage of cattle food	11.29 (20)	22.60 (40)	11.29 (20)	22.60 (40)	11.29 (20)	21.02 (37)	100 (177)
Loss of any trees, fruits, and vegetation	11.29 (20)	11.29 (20)	22.60 (40)	22.60 (40)	16.95 (30)	15.27 (27)	100 (177)
Reduction of any animal species	14.12 (25)	15.25 (27)	10.73 (19)	14.69 (26)	14.12(25)	31.09(55)	100 (177)

Levels: 1 = Highly Increase, 2 = Increase, 3 = Moderately Increase, 4 = Decrease, 5 = Highly Decrease (Source: Field survey, 2016)

forest biomes frequently align with patterns of climatic variables, notably temperature and moisture. In addition, 50% respondents of the study said that climate change has adverse effects for which forestland has decreased.

3.6.5 Shortage of Food and Increases in Commodity Price

People of the country depend on agricultural production for their food. Agriculture in Bangladesh relies heavily on weather conditions, and its production is anticipated to be notably affected by climate change-induced phenomena such as the spread of soil salinity, rising sea levels, tidal flooding, and intensified storm surges. The study reveals that 83% of the population recognizes food shortages due to the impacts of climate change. Also, 41.8% have recognized the losses level as increased which occupies the highest percentage. On the other hand, 12.99% respondents express it as moderately increase. Furthermore, 28.25% of respondents believe that food shortage has highly increased by climate change effects. However, 64% of the total respondents believe that the price increase is associated with climate change effects.

3.6.6 Shortage of Pure Drinking Water

Access to clean drinking water, in study areas, has worsened as the areas experience the detrimental impacts of climate change. A total of 60% opined that the drinking water shortage is due to climate change effects. On one hand, 18.65% of respondents assume that the problem has highly increased; in addition to this, 20.34% of people recognize it as an increase. On the other hand, 20.90% of respondents express it as a moderate increase. It is noted that groundwater salinity level during dry season to the depth of 50–100 m from the surface in the study areas. The mixing of saline water with groundwater is a contributory cause of the drinking water shortage and is believed by 48% of questionnaire participants. Hence, 14% of households find and explore that the level of mixing is increased by climate change resulting in the drinking water shortage. However, 23% of respondents have not found any effect of groundwater salinization on drinking water shortage.

3.6.7 Occupational Change and Lack of Job

Climate change has not only devastated the primary employment opportunities for rural residents but also has introduced new risks related to income and livelihoods. Despite the availability of human capital, there is insufficient demand for labor due to the scarcity of employment opportunities in the agricultural and fisheries sectors. More than 57% of respondents ranked the level of climate change effects on that of occupational change. A total of 29.95% among those surveyed it was reported as an increase. From the FGDs, affected people reported a reduced demand for human labor. Furthermore, employers take advantage and use this opportunity due to the wide availability of human labor and in doing so pay low wages or low salaries to labors. Climate change also has adverse effects on women's employment, as they face discrimination in terms of wages and working conditions.

3.6.8 Effects on Infrastructure

The intensified events triggered by climate change pose significant threats to existing physical infrastructure. Poorly constructed houses and sanitation facilities are particularly susceptible to the devastating impacts of natural disasters. As a result, human settlements face significant vulnerability to floods and cyclonic storm surges worsened by climate change. This study suggests that 75% of people acknowledge the effects of climate change on the infrastructure. However, 44.63% of people have recognized the loss level has increased, which is the highest percentage found in this part of the questionnaire. It has been mentioned as having increased by 17.51% by respondents. On the other hand, 12.99% of respondents express it as a moderate increase.

3.6.9 Climate Change Effects on Health

There is insufficient information available to fully comprehend the effects of climate change on human health. Climate variability is closely associated with the activity of pathogens (Mora et al., 2022). Conversely, scientific evidence strongly indicates that climate change has various impacts on human health, spanning from heightened risks of weather events and increasing sea levels to changes in infectious disease dynamics (Mora et al., 2022). Wu et al. (2018) identified the relationship between heatwaves, precipitation, and tree cover and that of Cholera in Bangladesh. Under climate change, the occurrences of diseases caused by pathogens are expected to rise. Malaria and dengue fever are widespread in Bangladesh. The rise in surface temperatures could potentially facilitate the spread of vector-borne diseases carried by mosquitoes. Consequently, life-threatening diseases like malaria and dengue present increased risks to human health as a result of climate change. The findings suggest that 83.05% of people believe that diseases have increased in recent years due to climate change as indicated in the study area. However, 13% suggest that they did not note any change in the disease pattern due to the impacts of climate change. The remaining 4% could not respond to the question.

Table 6 Diseases observed in the study area

Disease types	Frequency	Percentage
Asthma	118	27.45
Dengue	58	13.48
Malaria	59	13.72
Skin	144	33.49
Diarrhea	25	5.81
Others	26	6.05
Total	**430**	**100**

Source: Field survey, 2019

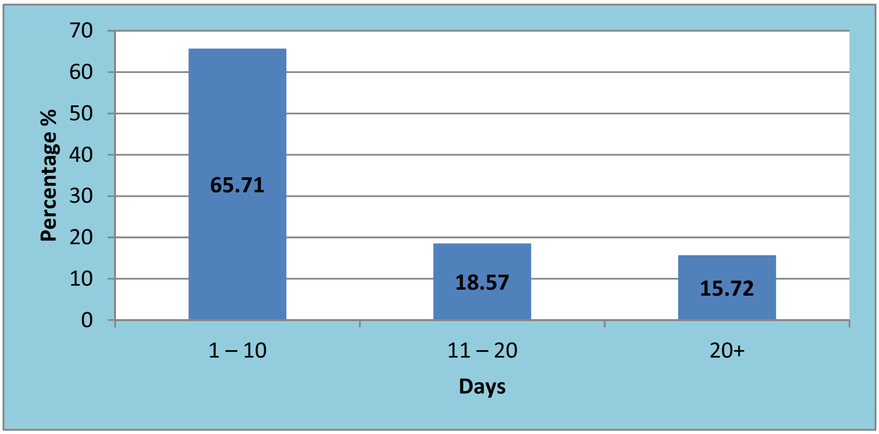

Fig. 5 Duration of waterlogging problems (Source: Field survey, 2019)

It was observed that derma logical skin health impacts were the most suffered disease in the study area (Table 6). Also, 33.49% of participants have experienced skin-related diseases due to the effects of climate change. Additionally, asthma affected a significant portion (22.45%) of the population in the study area. Other prevalent diseases in the area included dengue fever (13.48%), malaria (13.72%), and diarrhea (5.81%).

3.7 Climate Change and Waterlogging

The issue of waterlogging can pose a greater threat than that of flooding, especially in coastal areas where a sustainable drainage network system has not been established. The severity of this problem is progressively escalating, resembling a growing catastrophe. When residents of the study area were questioned about the incidence and impacts of waterlogging, the findings revealed that 79.09% of the respondents experienced waterlogging issues, primarily caused by cyclones and increased rainfall, both of which are consequences of climate change. Among the households surveyed, 65.71% endure waterlogging-related challenges for up to 10 days at a time (as depicted in Fig. 5). Another 18.57% endure even greater hardship, grappling with waterlogging for a duration ranging from 10 to 20 days. The most vulnerable segment, constituting 15.72% of the population, copes with waterlogging problems that persist for more than 20 days.

4 Conclusion

This study delves into the intricate empirical landscape of how the coastal population of Noakhali, Bangladesh perceives climate change, its profound impacts on their daily lives, and the strategies they employ in order to adapt. The individuals in this study area grapple with significant socio-economic challenges, characterized by widespread poverty, limited access to education, and subsistence-level livelihoods. Most of them rely on small-scale farming which produces meager incomes. These communities are directly facing the tangible effects of climate change, which are reshaping their agricultural practices and overall well-being. The most conspicuous symptoms of climate change, as observed by the majority, include a noticeable increase in both rainfall and temperature (14.12%), shifts in the timing of rainfall (10.17%), the emergence of prolonged and scorching hot summers, delayed winters, and extended monsoon seasons. Additionally, they are confronted with escalating occurrences of floods, cyclones, storm surges, salinity intrusion, and riverbank erosion. These climatic changes are the primary drivers of environmental instability in the study area.

The agricultural sector bears the brunt of climate change, with substantial losses resulting from crop diseases, pest infestations, and the depletion of soil nutrients and fertility. These factors are pivotal in exacerbating food security issues and reducing crop diversity. This loss extends to various crops, vegetation, and animal species, contributing to a decline in biodiversity. Furthermore, the adverse effects of climate change manifest in deteriorating public health, with a significant 83.05% of respondents reporting an increased incidence of diseases. These health concerns are predominantly centered around skin diseases (33.49%) and asthma (27.45%). Waterlogging, brought about by the changing climate patterns, presents an additional challenge, making daily life increasingly arduous for the local populace.

The study underscores the critical need for key stakeholders, including NGOs, government entities, and donor agencies, to take proactive measures aimed at mitigating the adverse effects of climate change in the region. This should encompass the initiation of educational programs tailored to the coastal population, focused on enhancing their comprehension of climate change's impact and the implementation of scientifically grounded adaptive strategies. Such initiatives are integral in elevating the community's awareness and perception of climate change effects. Moreover, it is crucial to engage locals in the decision-making process, ensuring their engagement in crafting climate adaptation policies. A sustainable plan for climate change adaptation must integrate local knowledge, as it is often deeply rooted in the region's unique challenges and opportunities. The multifaceted nature of adaptation demands a holistic, multidisciplinary approach, addressing diverse aspects of the issue. To effectively mitigate climate change's effects, investing in capacity building for vulnerable populations, both in terms of practical adaptation measures and their understanding of climate change, is of paramount importance. By taking these steps, we can work toward building resilience and fostering a more sustainable future against changing climate.

Contributions **Edris Alam:** conceptualization, data collection, analytical procedures, securing funding, research exploration, methodological approach, project oversight, initial drafting, revision and refinement, software utilization. **Md Imtiaz Uddin:** data management, in-depth analysis, initial drafting, revising, and editing, software utilization. **Morshed Hossan Molla:** conceptualization, original drafting, reviewing, and editing. **Mohammad Mohaiminul Islam:** statistical analysis, research methodology, initial drafting, revision, and editing. **Sumon Miah:** statistical analysis, initial drafting, revision and editing, data management, software utilization. **Paul Donald Johnstone:** data management, research methodology, initial drafting, revision, and editing, **Tanvir Mahtab Nasim:** research exploration, methodological approach, initial drafting, revision, and refinement. **Md Azizul Hoque:** conceptualization, initial drafting, revision, and editing. **Nadia Afrin:** original drafting, reviewing, and editing.

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HVDC Submarine Cable: A Perspective towards Accomplishing UN's SDGs for Indian Marine Ecology

S. Parveen, D. Mishra, and D. Mishra

1 Introduction

Power transmission between countries, often referred to as cross-border or international power transmission, involves the exchange of electricity between neighboring or distant countries for various reasons, such as ensuring a stable energy supply, accessing renewable energy sources, and promoting economic cooperation. Infrastructure, such as high-voltage transmission lines, substations, and converter stations, is required to transmit electricity between countries. Submarine cables are used when they need to be transmitted across bodies of water, such as seas and oceans (Ardelean & Minnebo, 2015; Europacable, 2011). Submarine cables are indispensable for connecting offshore wind farms to onshore grids and connecting islands with mainland grids.

The production and transmission of power lead to marine pollution. Marine pollution introduces unfavorable substances or pollutants into the marine environment, adversely affecting marine ecosystems, human health, and the economy. Oil spills, chemical discharge, marine debris, and shipping activities are many reasons for marine pollution. Alongside these, one of the major marine carbon contributors is electric power generation through submarine/subsea cables and transportation (Europacable, 2011; Tayal et al., 2002). The demand for power is increasing steadily, invariably increasing the burden of CO_2.

S. Parveen (✉)
Indian Maritime University, Kochi Campus, Kochi, Kerala, India
e-mail: shabnamparveen@imu.ac.in

D. Mishra
Future Institute of Engineering & Technology, Bareilly, India

D. Mishra
Indian Maritime University, Kolkata Campus, Kolkata, West Bengal, India

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The ambitious goal of the greenhouse gas emission (GHGe) strategy was adopted by the International Maritime Organization (IMO) in 2018 (Ekwere, 2016; Tayal et al., 2002; Vanessa, 2021). The strategies emphasized reducing GHG emissions to 50% of their 2008 levels. IMO 2021 has a target of reducing carbon dioxide by 1.5% annually from 2023 to 2026. The United Nations Convention on the Law of Sea (UNCLOS) of 1982, the Geneva Conventions of the Continental Shelf and High Seas 1958, and the International Convention for the Protection of Submarine Cables 1884 are some of the regulatory bodies that play crucial roles in preventing, monitoring, and mitigating marine pollution caused by subsea cables. As part of the 2030 Agenda for Sustainable Development of Marine Ecology, Sustainable Development Goals (SDGs) SDG 7, SDG 13, and SDG 17 are directly associated, whereas SDG 3 and SDG 15 rely on the other three to install subsea cables (Ekwere, 2016; Tayal et al., 2002; Vanessa, 2021) (Fig. 1).

Environmental considerations are integral to subsea cable projects in the European Union (EU). The prime focus of the EU has been connecting offshore renewable energy sources, such as offshore wind farms, to onshore grids through subsea cables. This will help in transmitting clean energy and subsequently contribute to its renewable energy goals. The NorNed Subsea DC connector, SAPEI, and HVDC Cross-Channel are some of the existing subsea projects of the EU that cover the huge water bodies of the North Sea, Baltic Sea, English Channel, and Tyrrhenian Sea (Ekwere, 2016; Europacable, 2011; Tayal et al., 2002; Vanessa, 2021).

Several countries on the Indian subcontinent, including India, Bangladesh, Nepal, Bhutan, and Sri Lanka, have been exploring cross-border power transmission projects using high-voltage technology. These projects aimed to share electricity resources, promote regional energy security, and support economic development. These projects require substantial infrastructure investment, including the construction of HVDC converter stations, substations, and transmission lines. India and Sri Lanka have explored the possibility of interconnecting their power grids through an HVDC submarine cable (May et al., 2016; Meah & Ula, 2007; Xiang et al., 2016). In India, overhead HVDC cables play a vital role in ensuring a reliable supply over long distances. The large-scale construction of overhead HVDC lines has harmful

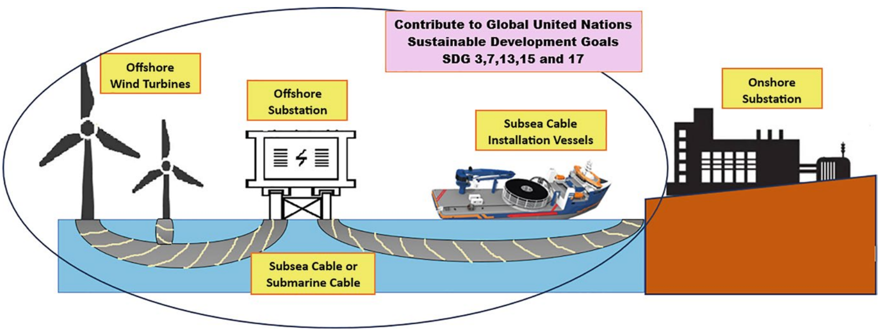

Fig. 1 Power transmission using HVDC submarine cables

effects such as the risk of fire, concerns related to health, electrical interference, and environmental impact when involved in cross-border connectivity.

2 Performance Analysis of HVDC and HVAC for Submarine Cables

Various high-voltage (HV) technologies capacitate the requirements of a sustainable future. High-voltage direct current (HVDC) and high-voltage alternating current (HVAC) transmission systems are two distinct technologies that can be used in service for a range of 35 kV to 800 kV (Jeroense, 2008; Jeroense, 2010; Ludin et al., 2022; Mazzanti, 2022). The transmission distance, losses, and grid synchronization are some parameters considered for determining the suitability of HVAC or HVDC transmission at any location. HVAC is typically used for regional or national power grids, city-level distributions, and industrial applications with moderate distances between power generation and consumption (Ekwere, 2016). From Figs. 2 and 3, it is well understood that, in comparison with HVAC, HVDC might be complex and has a high capital cost, as it incorporates an aggregation of AC/DC converters, but considering the technical specifications, it has comparatively low power losses over long distances (Meah & Ula, 2007; Vanessa, 2021). The nonexistence of induced losses in armoring neighboring cables and metal structures gives better utilization (kV/mm) in HVDC cables (Coleman et al., 2015; Jeroense, 2010; Schavemaker & Sluis, 2008; Wang et al., 2021).

According to studies for a cable length of 1000 km carrying power of 3000 MW at 800 kV, the loss percentage of HVAC transmission cables is 6.7% and that of HVDC cables is 3.5% (Jeroense, 2008). When the cable length increases to 2000 km while keeping all other features the same, the loss percentage for the HVDC cables is half that of the HVAC cables. HVAC cables use materials optimized for the rapid reversal of the electric field that occurs in AC systems, focusing on minimizing partial discharge and heat-related issues. On the other hand, HVDC cables require materials that can withstand continuous DC operation and manage space charge accumulation. The number of power lines required in HVAC is 3, whereas in HVDC, it is just 1 (or 2). Hence, the amount of conducting material required to transport the same amount of electricity is less in HVDC than in HVAC. Submarine cables are vital components of the global energy infrastructure, facilitating long-distance cross-border or intercontinental power transmission, for which HVDC has proven its merit over HVAC. Fig. 4 shows the relationship of the total terminal cost for

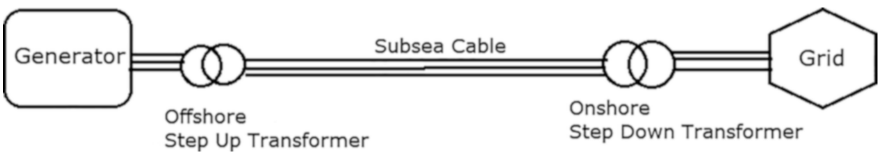

Fig. 2 Basic structure of an HVAC submarine power transmission system

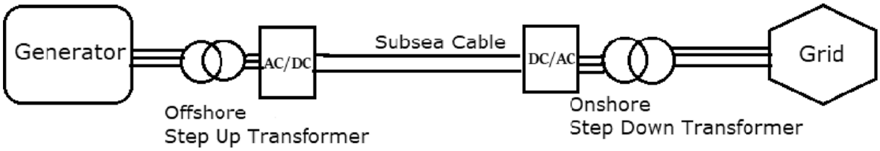

Fig. 3 Basic structure of an HVDC submarine power transmission system

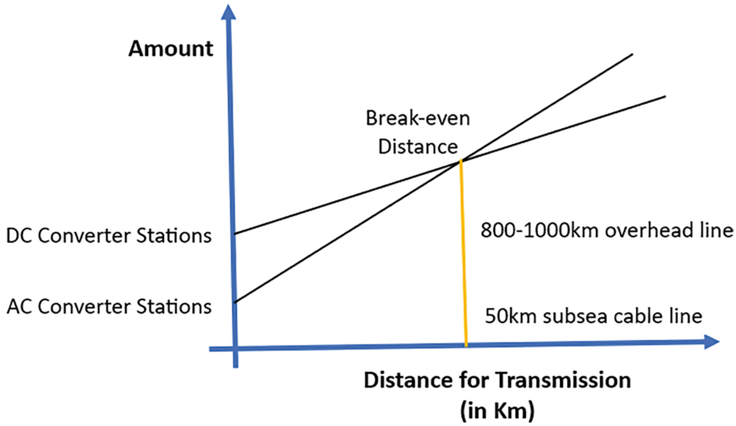

Fig 4 Cost analysis of HVAC vs. HVDC transmission technology (Meah & Ula, 2007)

investment in the transmission system over the route distance of the cable. Although the initial cost of investment in HVDC transmission technology is high compared with that of an HVAC transmission technology, over longer distances, it is incredibly economical. The break-even distance is different for subsea cables and overhead lines, and it also varies with projects of different locations (Coleman et al., 2015; Jeroense, 2008; Nishikawa et al., 2017; Schavemaker & Sluis, 2008; Wang et al., 2021).

3 Subsea Cables for a Carbon Neutral Energy System in the Indian Subcontinent

According to some studies in the early 2000s, the "per unit weight" power (P_{HVDC}) transported by any extruded subsea cable (HVDC) ranged between 20 MW/kg and 50 MW/kg (Jeroense, 2008). On the other hand, the "per unit weight power" (P_{HVAC}) carried by an extruded submarine cable (HVAC) varies between 10 MVA/kg and 20 MVA/kg (Jeroense, 2008; Mazzanti, 2021; Wang et al., 2021; Zhou et al., 2020). Depending on the cable design and cross section, these ranges can vary.

In this way, the assumption for the "per unit weight" power for subsea cables is given by

$$\text{Average } P_{HVDC} = \frac{50 + 20}{2} = 35\,\text{MWkg}^{-1}$$

$$\text{Average } P_{HVAC} = \frac{20 + 10}{2} = 15\,\text{MWkg}^{-1}$$

These are some rough estimates that are taken for the future prediction of CO_2 emissions (Mazzanti, 2022; Vanessa, 2021). The utilization of HVDC vs. HVAC cables is estimated by determining the quantity of renewable energy carried for 2 years (h_{2yrs} = 17,520 h) of performance by a cable of unit weight (1 kg).

Therefore, for an HVDC, the amount of clean energy can be obtained by Eq. (1):

$$W_{HVDC} = h_{2\text{yrs}} \times \text{Average } P_{HVDC} = 17{,}520 \times 35 = 6.13 \times 10^5 \left[\text{MWh / kg}\right] \quad (1)$$

Similarly, for HVAC, the amount of clean energy can be obtained by Eq. (2):

$$W_{HVAC} = h_{2\text{yrs}} \times \text{Average } P_{HVAC} = 17{,}520 \times 15 = 2.63 \times 10^5 \left[\text{MWh / kg}\right] \quad (2)$$

It is clear from Fig. 5 that in India, the amount of GHGe due to electricity generation is around 0.790 tons (CO_2) e/MWh; therefore, the amount of GHGe set aside in 2 years can be given by

$$GHG_{HVDC} = W_{HVDC} \times GHGe = 6.13 \times 10^5 \times 0.790 \left[\text{tons / kg}\right] = 4.842 \times 10^5 \left[\text{tons / kg}\right] \quad (3)$$

$$GHG_{HVAC} = W_{HVAC} \times GHGe = 2.63 \times 10^5 \times 0.790 \left[\text{tons / kg}\right] = 2.077 \times 10^5 \left[\text{tons / kg}\right] \quad (4)$$

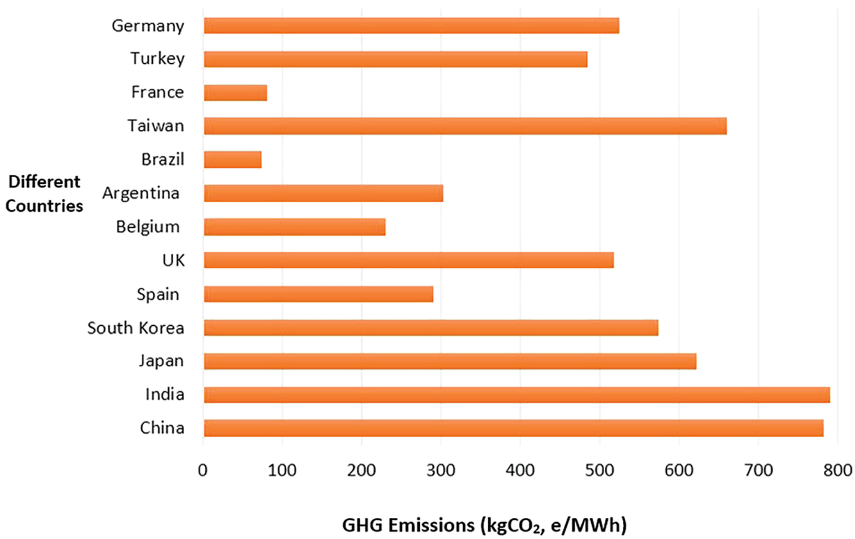

Fig. 5 Life cycle of emissions of greenhouse gases (GHGs) from electricity generation for various countries (Coleman et al., 2015)

From Eqs. (3) and (4), it can be put forward that the "per-unit-weight of cable" of rescued GHG yearly for any HVDC extruded cable is appreciable, and it is estimated to be nearly a multiple of two in comparison with the amount of GHG rescued in a year with the HVAC extruded cable.

4 Challenges for Various Types of HVDC Submarine Cables

HVDC cables are of several types, but in general, two variations of transmission cable systems widely exist for HVDC: extruded cables and paper-insulated cables.

Since the 1950s, paper-insulated mass-impregnated (MI) cables have been very popular (Schavemaker & Sluis, 2008). MI cables are traditional and still the most widely used type of submarine cables. The construction of these cables involves wrapping the conductor with multiple layers of insulation and impregnating them with a liquid dielectric material, improving their electrical properties. While MI cables offer many advantages, such as high reliability, low transmission loss, cost efficiency, and lightweight, they simultaneously also experience many drawbacks, such as the prolonged time required for jointing (Ludin et al., 2022). From Fig. 6, it can be clearly affirmed that over the years, MI cables have become more popular.

Over time, the insulating material inside the cable can degrade and break down, reducing the dielectric strength of the cable and increasing electrical leakage. If the outer layer of a cable is damaged, seawater can penetrate the cable and displace the dielectric fluid, leading to a decrease in the insulation performance of the cable and an increased risk of cable failure.

Extruded submarine cables can resist an operational temperature higher than that of MI cables. To date, the HVDC extruded cable has been operational at approximately 300 kV, but its augmentation is possible and it was even announced by ABB in 2015 (Jeroense, 2008). These cables consist of a solid or stranded conductor

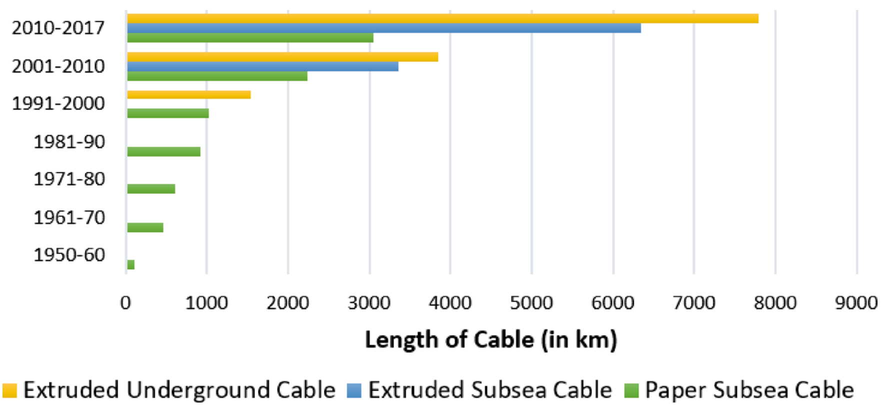

Fig. 6 Advancement of extruded cables and mass-impregnated cables over the years (Chen et al., 2015)

surrounded by a single layer of extruded insulation material, such as cross-linked polyethylene (XLPE) or ethylene propylene rubber (EPR). As per the existing literature, oil-impregnated paper-based power cables and cross-linked polyethylene (XLPE) cables have recently gained popularity for offshore power generation and transmission because of their higher current conduction capacity, better mechanical support and high insulation stability in the presence of chemical agents (Mazzanti, 2021; Nishikawa et al., 2017; Wang et al., 2021; Zhou et al., 2020). Various researchers have reported that several parameters significantly influence the performance of submarine cables (Jeroense, 2008; Mazzanti, 2021; Wang et al., 2021; Zhou et al., 2020). These parameters include the accumulation of space charge, effect of moisture, and fishing.

Space charge is a phenomenon that occurs in the insulation material of HVDC cables. When an HVDC cable is energized, a high electric field is generated in the conductor. A good dielectric material is supposed to have a very low value of stored charges. Because of the nonhomogeneity of the insulation material, there is a nonuniform flow of charges and, at times, accumulation in certain regions of the insulation, creating a space charge (Zhou et al., 2020). Space charges in HVDC cables can have several undesirable effects on the cable performance. It can alter the electric field distribution, leading to nonuniform stress on the insulation material. This can magnify the risk of electrical breakdown and reduce a cable's lifespan. Additionally, space charge can cause partial discharge (Mishra et al., 2020), which can lead to insulation degradation and eventual cable failure.

For insulation in an HVDC cable, the electric stress is given by Eq. (5):

$$E(d) = \frac{V}{d \ln\left(\frac{r_c}{r_s}\right)} \tag{5}$$

Here, r_c and r_s represent the radii of the conductor and sheath, respectively while d signifies the radial distance.

The cable design and the environmental conditions for laying the HVDC cables play a crucial role in the rate of transportation of power. A deeply laid and closely spaced cable in the ground with high thermal resistivity in a warm country will have a smaller power transportation rate than a pair of cables with contrasting climatic situations. Hence, the implementation of HVDC cables should be encouraged. Still, due to the variable climatic conditions around the year, the comparative study of GHGe with respect to power generation will be variable for India compared with other cold countries in Europe. Along with temperature, other parameters such as the salinity of water, hydrostatic pressure, and seabed type significantly influence the insulation condition.

Figure 7 shows that as the temperature decreases inside the water, the salinity increases. This high salinity, coupled with water, shows high conductivity, which significantly influences the performance of submarine cables. Thus, from the above discussion, it can be opined that if reliable operation of submarine cables can be achieved, it might be helpful for decarbonization.

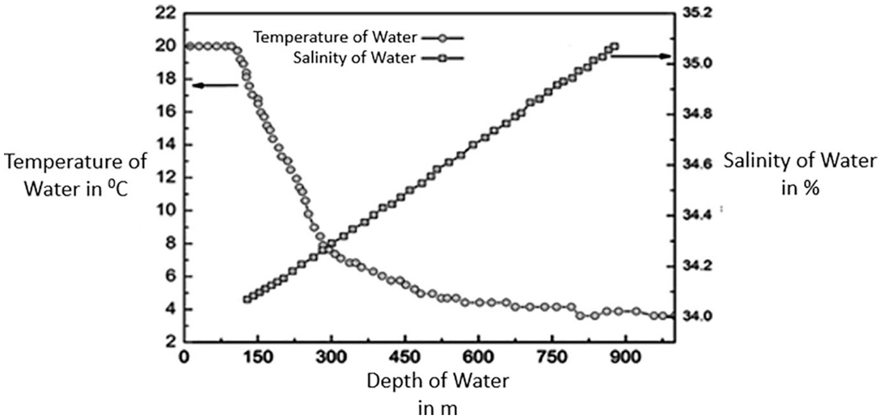

Fig. 7 Variations in temperature and salinity of seawater with depth (Wang et al., 2021)

5 Conclusion

With the augmentation of HVDC subsea cables, the European Union (EU) has significantly achieved lowered GHGe over the past two decades. The present Indian scenario that is ever more stressed by the ever-increasing emissions of GHG, the "per-unit-weight of cable" of GHG rescued yearly shows that HVDC subsea power transmission is a blend to transport sustainable energy to regions of utilization. Moreover, it strengthens the worthiness, credibility, and durability of interconnected HVAC/DC transmission grids. The role played by HVDC transmission cables will be fundamental in making a mix of achievable, cleaner, sustainable, and cost-efficient energy that has easy availability and accessibility. Achieving the aims of COP26 will be smooth, along with the wide implementation of HVDC.

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The Impact of Climate Change in the Eastern Himalayan State of Sikkim, India: A Review

Santosh Sharma, Ashish Kumar Arya, and Archana Bachheti

1 Introduction

Climate Change (CC) is defined as a statistically significant variation that lasts for a long time (typically decades or longer) in either the mean condition of the climate or its variability (Katz, 2010). The main cause of CC has been the release of greenhouse gas emissions from industry into the atmosphere as well as combustion from routine human activity. In this regard, the primary cause of the observed global warming since the middle of the twentieth century has been attributed to human population (IPCC, 2007). Due to the adverse impacts of CC on various spheres of human life and the different ecosystems of the Earth, it has become a major environmental concern that has attracted the attention of environmentalists, researchers, scientists, and policymakers globally. The effects of CC are long-lasting and affect physical infrastructure, food security, economic activity, natural resources, health, and society at large. Monitoring of average global temperature since the middle of the nineteenth century has revealed that there has been a 0.6 °C rise every century (Anjum et al., 2023). According to scientific reports, the temperature of air near the surface of the earth has increased on an average by 0.74 + 0.18 °C globally during the twentieth Century (Negi & Palni, 2010). The issue of CC has, at different times, been discussed either as a scientific (Edwards & Schneider, 2001; Pittock, 1995; Wigley & Raper, 2002), economic (Glantz, 1995; Nordhaus, 1994; Shih, 2000), or ethical (Broome, 1992; Jamieson, 1997; Müller, 2002). Nonetheless, only in 2007, its pervasive nature was known to the world with the revelation by the Intergovernmental Panel on Climate Change (IPCC) that CC was then undeniably

S. Sharma
Department of Management, The ICFAI University Sikkim, Gangtok, India

A. K. Arya (✉) · A. Bachheti
Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India

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taking place (Pachauri & Reisinger, 2007). The Earth's surface has grown steadily warmer over the last three decades compared to every other decade in the observational record, with the first decade of the twenty-first century being the warmest (Hartmann et al., 2013). Inevitably, CC has brought up new difficulties for the world's agricultural production, biodiversity, water availability, and human livelihood (Tambe et al., 2011; Tripathi & Singh, 2013; Uprety et al., 2017).

As far as mountain ecosystem is concerned, ecosystems at high-elevation zones experience more rapid temperature changes which make them susceptible to CC than ecosystems at low-elevation zones (Bhutiyani et al., 2007; Pepin et al., 2015). A large mountain range, the Himalayas, is recognized worldwide for its important contribution to regional and global climate control, which directly affects ecology, biodiversity, and ecosystem services that are essential to the survival of millions of people living in the Himalaya and surrounding areas (Negi et al., 2017). It is known to all the environmentalists that the mountain ecosystems are particularly sensitive to CC. It has previously been documented that the Himalayan region is warming three times as quickly as the world average (Kumar et al., 2008; Xu et al., 2009). The Himalayan region warmed by 0.06 °C each year between 1982 and 2006, a rate that is much greater than the world average warming of 0.85 °C between 1880 and 2012 (equal to 0.006 °C per year) (IPCC, 2013; Shrestha et al., 2012). As compared to 0.74 °C average increase inf temperature globally, there has been a 1.5 °C average increase in temperature in the Himalaya (Negi et al., 2021). In this context, An increase in temperature ranging from 0.28 to 0.80 °C per decade has been documented in the North-western Himalaya, while the Eastern Himalaya has experienced variation in temperature increase from 0.20 to 1.00 °C per decade (Negi et al., 2021). Furthermore, similar to other regions worldwide, the Himalaya are witnessing swift alterations in their climate, which could have a substantial effect on regional ecosystems, biodiversity, farming, and the welfare of human populations (Chaudhary et al., 2011). The life in the Himalayan region largely relies on monsoon weather and therefore may have prominent effects if there is any shift or change in rainfall pattern. Many floral and faunal elements are sensitive to temperature, rainfall etc. therefore, survival, regeneration, phenology etc. of these elements may directly be related to the weather of the area (Lepetz et al., 2009). Under these circumstances, phenological changes in plants might be among the first signs of a rapidly changing global climate (Rai, 2008). In the Indian Himalayan Region (IHR), climate patterns are changing and extreme weather events have increased which are attributed to the impact of CC (Eriksson et al., 2009). In the year 2022, extreme weather events were recorded on 88% of the days in the first 9 months of the year and the warmest March as well as the third warmest April in over a century in the year 2022 (Pandey & Sengupta, 2022). In the IHR, snow is melting quickly, water sources are drying out, and the weather has become irregular and unpredictable(Chaudhary et al., 2011; Chaudhary & Bawa, 2011; Sharma et al., 2009; Tambe et al., 2011). Unfortunately, research on how CC is affecting mountainous regions is fragmented, insufficient, and primarily conducted on a single subject (Anjum et al., 2023; IPCC, 2007; Nogues-Bravo et al., 2007; Sharma & Shrestha, 2016; Tambe et al., 2012). In fact, there are hardly any review studies on the effects of CC in Sikkim, the second smallest state in the eastern Himalayas of Indian Union(Acharya & Chettri, 2012). Keeping in view the impacts of CC in the IHR, the objective of the current study is to shed light on how CC has affected and may affect climate-sensitive sectors such as such as forestry, agriculture, water resources, disaster, and biodiversity. This would aid in the better understanding of the emerging challenges of CC in the study area. Furthermore, the present study also highlighted the important environmental initiatives in Sikkim for mitigating and combating the impacts of CC.

2 Study Area

Sikkim ($27^0 05'$ to $28^0 07'$N and $87^0 59'$ to $88^0 56'$E) as a part of the Eastern Himalayas is one of the smallest and least populated Indian states (7096 km^2 area) with the total population of 610,577 (2011 census) (Fig. 1). It is bordered on the north by the Tibetan Plateau (in China), on the east by the Chumbi Valley and the Kingdom of Bhutan, on the west by the Kingdom of Nepal, and on the south by the Darjeeling District of West Bengal. The third-highest mountain in the world, Mt. Khangchendzonga (8598 m), is situated in the northwest of the state. Sikkim has a

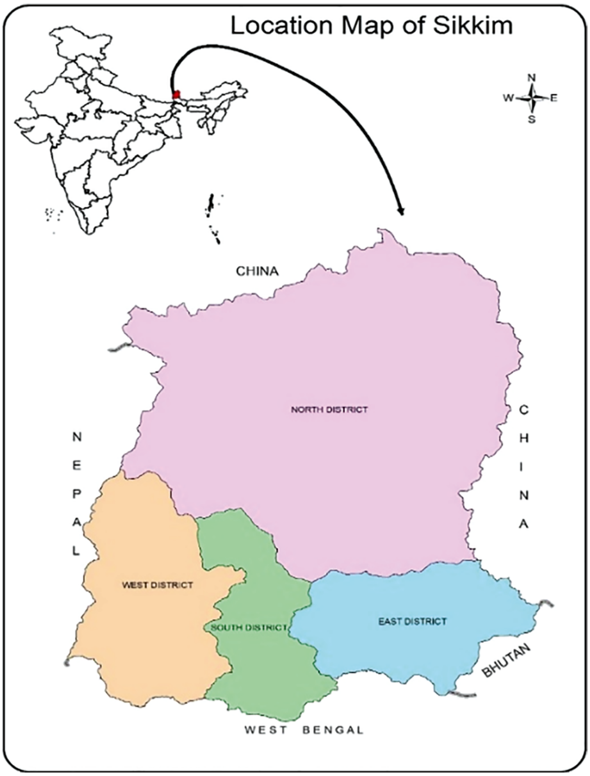

Fig. 1 Location of Study Area (Sikkim) in India

heterogeneous ethnic community mainly comprising Bhutia, Lepcha, and Nepali etc., making it culture rich state. Being a part of the biodiversity hotspot of the Eastern Himalayas, Sikkim has exceptionally rich biodiversity, a highly varied eco-climate, and significant altitudinal variation (300–8598 m) with 47% forest cover (Forest Survey of India, 2009; Mittermeier et al., 2004). Out of the total geographic area, forests cover 5452.40 km^2 area which includes pasture land (104 km^2); besides uncultivable alpine regions such as perpetual snow, glacier, and alpine lakes etc.

3 Methodology

The study focused on investigating the impacts of CC in Sikkim by gathering information from various secondary sources. We conducted a systematic review by examining published journal articles, books, technical reports, theses, government publications, and other sources available until 2023. We utilized Google Scholar and specific search terms related to CC and Sikkim for web-based searches in English using keywords like "CC," "Sikkim," and "impact." We collected relevant data and information pertaining to temperature trends, precipitation patterns, and other relevant data sets. A total of 160 literatures on CC in Sikkim were collected, and approximately, 80 were considered for review.

4 Results and Discussions

4.1 Rainfall and Temperature Patterns in Sikkim Himalaya

The Eastern Himalayan state of Sikkim is located in the Indian Himalayan Region (IHR), which is a fragile mountain range, and climatic change has been affected by CC in recent years. Temperature and precipitation are the two main meteorological indicators of a region's climate. Only two stations, Gangtok and Tadong in the East district, have four decades of reliable long-term meteorological data for the state.

Among all the mountain ecosystems in the Eastern Himalayas, Sikkim's relative CC vulnerability rating during the last decade has been determined to be 51 out of 89 (Tsering et al., 2010). Previous studies on the trend of temperature and precipitation data for Gangtok from 1957 to 2005 indicate a trend toward warmer nights and cooler days, with increased rainfall, except in winter (Tambe et al., 2011). It was observed in the last decade that the rainfall pattern in Sikkim had become erratic during the last few years compared with the long-period average from 1957 to 2005(Seetharam, 2012). Over the previous three decades, Gangtok's annual mean temperature has increased steadily, and the city's maximum temperature has been rising at a rate of 0.2 °C each decade. Meanwhile, the annual rainfall has been rising at a rate of over 50 mm per decade (Seetharam, 2008). In yet another research done by the Department of Science and Technology, Government of Sikkim Gangtok's temperature has increased from 1 to 1.5 °C since 1957 (Bhutia & Gurung, 2019). Observed CC in the state includes an almost 2.5 °C increase in minimum temperature between 1957 and 2009 (GoS, 2012). Sikkim has the highest increase in winter mean temperature across India (+0.05 °C/year) and witnessed a 250 mm decrease in total rainfall from 1983 to 2009 (GoI, 2013). When the trend during the previous few years (2006–2009) was compared with the meteorological data (long-term) available for the Gangtok station (1957–2005), it revealed an acceleration of similar trends, with winter being significantly warmer and drier (Tambe et al., 2011). Five-year climatic variability data from 2006 to 2010 indicated a significant decrease in rainfall in nearly every season, along with warmer nights and cooler days accompanied by a rise in Gangtok's minimum temperature and a decrease in its maximum temperature (Seetharam, 2008). Similarly, during the last decade, Sikkim witnessed its longest-ever seven-month record-breaking dry and warm winter in 2008–09 (Khawas, 2011). In the previous decade, the increase in the annual rainfall at Tadong (i.e. Gangtok) at the rate of 49.6 mm/decade from 1957 to 2005 was reported (Seetharam, 2008). Furthermore, Between 1981 and 2010, 50% of the year had rainfall that was higher than average, and 50% of the year had rainfall that was lower than average (Rahman et al., 2012). During the decade 1991–2010, the Tadong meteorological station recorded a 17.77 mm yearly drop in rainfall and an increase of 1.950C in the mean minimum temperature between 1981 and 2010 (Rahman et al., 2012). According to community observations, a period of 6 months from October to March saw almost no rainfall, which led to an increase in the frequency of rising forest fires, the drying up of spring water sources, and a decrease in the yield of winter crops and vegetables leading to the conclusion that subtropical belt (at elevations of 1000 m) of Sikkim experienced the effects of CC during last decade (Tambe et al., 2012). Another has shown that from 1901 to 2015, there has been a decline in yearly rainfall, with a greater shortfall during the monsoon season (Kakkar et al., 2022). From the ongoing account, it is evident that the gradual effects of global warming have been visibly felt and have been proved in the last two decades in the state of Sikkim (Parvendra et al., 2020; Sharma et al., 2014).

4.2 Impacts of CC on Different Sectors in Sikkim Himalayas

People who live in mountainous areas may be directly or indirectly impacted by changes in the climate since they depend largely on climate-sensitive natural resources for their livelihood (Savo et al., 2016; Van Gevelt et al., 2019). CC can have immediate or long-term, direct or indirect effects. The impact of CC has the potential to break the socioeconomic as well as the livelihood support system linked to climate-sensitive sectors (agriculture, livestock, forestry) and their interlinkages and interdependencies with each other. The adverse impact of CC in Sikkim Himalaya is summarized below:

4.2.1 Forests

Climate of a place determines the vegetation patterns, distribution, structure, composition, and ecology of forests. In the IHR, forests in the Western Himalayas are extremely vulnerable to CC, whereas forests in the Eastern Himalayas are thought to be more resilient (Tripathi et al., 2022). According to one of the studies on the effects of CC on Sikkim's forest sector over the past 10 years, the state's forest sector is not expected to suffer short- or medium-term effects from CC. However, it is essential to conduct assessments of climate change consequences at decentralized levels using different climate scenarios and vegetation models, while considering the diverse limitations inherent in these models (Ravindranath et al., 2012). In the Singalila National Park of Khangchendzonga Landscape, Eastern Himalaya, changes in climate conditions, particularly temperature and rainfall patterns, were observed to correlate with shifts in vegetation distribution across the altitude gradient (Sinha et al., 2018).

4.2.2 Agriculture and Livestock

Earlier studies have concluded that more than 64% of the population of Sikkim depended on agriculture for their livelihood (Subba, 2009). Maize, paddy, wheat, barley, and buckwheat are the main cereals grown in Sikkim, and cardamom and ginger are the two important cash crops. The farmers of Sikkim practice mixed farming of agriculture, horticulture, and livestock rearing. The livelihood of the rural population of Sikkim is linked to agriculture and forest products that are climate-sensitive. CC as a threat to the biodiversity of Eastern Himalayas has been reported before (Bhattacharya, 2019). The agriculture sector is highly dependent on the climate and given that the population growth continues to occur, CC is likely to have serious consequences for Sikkim's agriculture.

Agroforestry ecosystems in the high-altitude regions of Sikkim Himalayas including those in eastern Nepal, Bhutan, Arunachal Pradesh, and the Tibetan Autonomous Region are extremely susceptible to CC (Tsering et al., 2010). The quality of fruits and vegetables is deteriorating due to frequent rains and hailstorms, and decreasing water availability for crop production has resulted in unstable crop yields (SAPCC, 2013). The adverse effect on the maize yield is projected to happen with the maximum and minimum temperature expected to increase and precipitation is expected to decrease in the future(Deb & Babel, 2015). There has been a drastic decline in the production of large cardamom (*Amomum subulatum* Roxb.) over the past few decades due to CC in Sikkim (Lepcha et al., 2023). Due to factors including temperature rise, unpredictable rainfall, shifting rainfall patterns, and an increase in conflicts between people and wildlife, many farmers have turned to other industries like tourism. Obviously, the CC could dent Sikkim's organic mission prospects in the near future if adaptive and mitigation measures are not implemented (Plate 1).

4.2.3 Water Resources

The immediate impacts of CC are generally experienced through the medium of water (IPCC, 2014; Olmstead, 2014). Floods and droughts are the immediate and visible impacts generally associated with CC (Goodess, 2012). Subsistence agriculture in mountainous regions where irrigation infrastructure is limited or absent and dependent on natural rainfall and spring water is likely to be among the most vulnerable to CC and variability (Misra, 2012; Panwar, 2020).

Plate 1 Typical agroforestry system at Sirwani, East Sikkim (14.01.2016)

Although the number of springs that have vanished from the various landscapes has not been scientifically and officially counted, there is ample evidence of a decline in the quantity of spring water sources throughout the state of Sikkim. The natural springs in the mid-hills of Sikkim becoming seasonal with reduced discharge have been reported before (Rahman et al., 2012). According to research conducted over the past 10 years, there were once a fair number of springs between Rangpo and Gangtok, but only two—one at Martam and the other at Tadong—remained (Poudyal, 2009). However, the discharge has noticeably reduced. The evidence of decline in spring water discharge in Sikkim during the dry season have been reported (Tambe et al., 2009; Sharma, 2010; Tambe et al., 2012). Spring studies carried out in Sikkim provide increasing evidence of drying of springs or becoming seasonal which could directly or indirectly have a deep impact on the economy and livelihood of the communities (Azhoni & Goyal, 2018; Bhutia & Gurung, 2019). At *Balakhola(River)* (1215 m), in the mid-Himalayan Taktsom Chu watershed, Assam Lingzey, East district of Sikkim, rainfall and runoff studies using the area-velocity method between 2009 and 2012 showed an increase in runoff from August to October, with runoff remaining relatively constant during the remaining months(Sharma, 2013). Precipitation in the form of rainfall at regular interval is very crucial as the spring sources are dependent on the rainfall that enables the recharge of mountain aquifers. Nevertheless, some studies have concluded that there has been a shift in precipitation patterns in recent years and predicts an increasingly erratic rainfall pattern in the near future in Sikkim Himalayas (Government of Sikkim, 2012; Singh & Goyal, 2016). This may result in further drying up of springs and a decline in the flow of water in rivers thereby affecting the sociocultural and economic life in the different regions of the state of Sikkim in many ways.

4.2.4 Biodiversity

Human-induced climate change is widely regarded as a primary factor driving the current mass extinction, significantly elevating the risk of extinction by 100 times compared to natural rates (Maxwell et al., 2016; Pimm et al., 2014; Shivanna, 2020).

CC as a threat to Eastern Himalayan Biodiversity has been reported before (Bhattacharya, 2019).

In Sikkim, due to the impact of CC, there have been warmer winters, very short spring, and long spells of rainy season. In response to CC, many species of faunal group have extended or shifted their ranges upwards along the elevation gradient in Sikkim. Since de Nicéville last saw the *Symbrenthia silana* butterfly at 600 msl in 1885, it was believed to be extinct. However, a sighting of the species was made approximately again at 1000 msl at Dzongu, North Sikkim (Kunte, 2010). The observation at higher altitudes could be attributed to alterations in its habitat brought forth by climatic shifts from the late 1800s (Kunte, 2010). In avian taxa, the house sparrows *Passer domesticus*, which was only found at low-lying places like Melli in South Sikkim, was also frequently observed in subtropical regions of Gangtok(NBSAP, 2012).(Plate 2). On the contrary, the avian species of low-elevation zones of Sikkim such as Singtam and Rangpo are also vulnerable due to the combined effect of urbanization and CC (Plate 3). There has been a significant influence of CC on Sikkim's faunal richness, which might have major repercussions including the extinction of species, according to earlier research on the effects of CC on animal diversity, specifically birds, reptiles, amphibians, and butterflies (Acharya & Chettri, 2012). Amphibian breeding activity has been impacted by drying springs and irregular rainfall patterns, leading to a decrease in the amphibian population (Acharya & Chettri, 2012). Tree line shifts and the ensuing invasion of woody species on alpine meadows were studied by ICIMOD, Nepal in 2009. The alarming rise in tree line in the eastern Himalayas at a rate of 5–10 m per decade was one of the findings in the reports that ICIMOD, Nepal examined in 2009 (Badola, 2009). The majority of endemic and vulnerable bird species can be found in temperate broadleaved forests (1800–2800 m) and broadleaved tropical forests

Plate 2 House sparrow *(Passer domesticus)* collecting nesting material during the start of breeding season, Gangtok (25.02.2014)

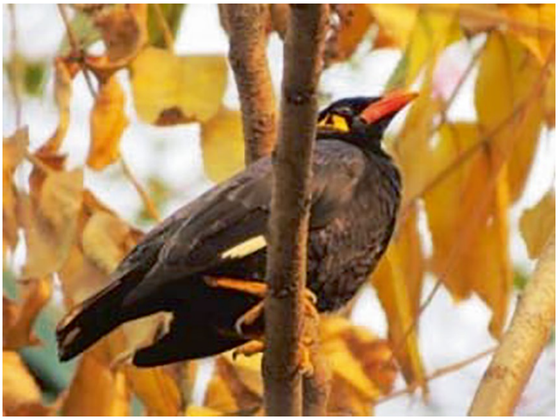

Plate 3 Common Hill Myna *Gracula religiosa* Singtam, East Sikkim has a declining population trend IUCN (2016) (12.01.2016)

(900–18,000 m above sea level). There has been a reduction in their habitats, which was caused by both direct human influence and CC (Acharya & Vijayan, 2010). In a recent study, significant changes in bird species richness, with a notable increase in bird species diversity, have been projected for regions above 2500 m elevation in Sikkim, northeast India, as well as the western Himalayas and the Western Ghats regions by 2070 (Deomurari et al., 2023).

A number of alpine plant species in the Sikkim Himalaya are experiencing increased environmental stress as a result of their biological reactions to CC (Telwala, 2012). According to Kumar (2011), the ideal bioclimatic envelope for rhododendrons has significantly decreased based on a CC projection scenario. According to a study conducted in the Parvati valley in Himachal Pradesh's subalpine region, the decline of *Betula* and its broad-leaved relatives and the emergence of arid components like *Juniperus* and *Ephedra* are signs that the climate change declined *Betula* in the most recent period(Chauhan et al., 2022). The distribution of invasive alien species in Sikkim Himalaya, including *Ageratum conyzoides, Chromolaena odorata, Lantana camara, Bidens pilosa,* and *Mikania micrantha,* has largely been due to rise in temperature. These species pose a serious threat to the native plant community and will ultimately lead to the depletion of plant diversity (Verma et al., 2023). Already *Eupatorium* sp. and *Parthenium* sp. have spread over large areas in the mountains and along roads and rivers (Singh et al., 2010).

The Sikkim Himalayas are a remarkable repository of biodiversity, home to several native, rare, threatened, endemic, and endangered floral and faunal species. Thus, it is necessary to conduct extensive research on how CC is affecting Sikkim's Himalayan biodiversity.

4.2.5 Disaster

In the Himalayas, natural disasters including avalanches, flash floods, and cloud bursts are occurring more frequently due to CC (Joshi et al., 2024). Extreme rainfall events brought on by CC caused several landslides and flash floods between 1990 and 2010 (Sharma et al., 2010; Sharma & Joshi, 2011). Similarly, reports from 2009 to 2011 indicated that forest fires started in several parts of Sikkim as a result of global warming, especially in lower elevation locations like the vicinity of Singtam and Rangpo(Sharma et al., 2012 and 2014). The state is already experiencing a rise in the number of landslides, rock avalanches from unstable slopes, and flooding. Construction projects intended to advance development have also contributed to landslides and rock avalanches from unstable slopes (Plate 4).

In the Indian Himalayan Region (IHR), CC is associated with the melting of the snow and glaciers or erratic weather patterns. There are reports that the lifecycle of glacier in the Himalayan region has been considerably impacted by climatic change and its variability (Lama & Devkota, 2009). Besides, the continuous growth of numerous glacial lakes has also been reported on the north face of the Kangchengyao massif of Sikkim Himalaya between 1988 and 2014 (Debnath et al., 2019).

In Sikkim Himalayas also, the impact of CC on glaciers has been reported earlier as per the reports published by *ENVIS* Centre Sikkim (2009)**.**

(I) A British expedition team noticed that, during their 28-day trip to the Goechala-Green Lake, the glacier sceneries at Zemu, Thongsong, and Talung had irreversibly changed during the previous 80 years.

(II) The Thongsong and Talung glaciers were separated, and as a result of global warming, the thickness of the snow covers on both glaciers has decreased over time.

The increase in glacier retreats is said to be due to temperature rise and anthropogenic activities over this region (Bhardwaj, 2020). Scientific studies conducted a decade ago in West Sikkim revealed that the East Rathong glacier has receded by 460 m over the previous 33 years (Luitel et al., 2012). However, the East Rathong Glacier's average retreat rate is smaller than that of similar Himalayan glaciers in the Western Himalaya, at 13.3 m/y (Luitel et al., 2012). Numerous studies have underlined that CC poses a severe threat to the Himalayan state of Sikkim since the region's northern glacier-covered mountains contain more than 315 glacial lakes, which could potentially result in glacier lake outburst floods, as has been documented in the last 10 years (Government of Sikkim, 2012; Jain et al., 2013; Shukla et al., 2018; Sattar et al., 2021). The potential risk of GLOF in the Teesta Valley at

Plate 4 Slope instability due to construction activities at Gangtok, Sikkim (2.1.2024)

Chungthang, North Sikkim due to South Lhonark Lake and therefore the need to conduct a full environmental impact assessment and potentially undertake GLOF risk mitigation measures was highlighted by earlier studies (Sattar et al., 2021). Nonetheless, no risk mitigation measures was in place and so the GLOF event of October 4, 2023, at South Lhonark Lake, North Sikkim which destroyed the hydro-projects at Chungthang and Dikchu and Sirwani and caused the loss of life of many people and damage to property is a case in point in this regard. With the increase in glacial lakes from 169 (1992) to 261(2015), the Sikkim Himalaya glacier has receded by 22 ± 6% (Kumari & Middey, 2023). Few years ago, a two-year study conducted in the isolated location of Lachung, North Sikkim, from 2018 to 2020 revealed that carbonaceous and sulfate aerosols were substantial contributors to the atmosphere (Arun et al., 2021). Using multi-temporal satellite Images, a recent study in the North Sikkim district tracked lake growth in the region, revealing that 203 new lakes had developed during the observation period (2000–2018), out of which 82 lakes had formed during 2011–2018 alone; indicating marked glacial retreat and consequent lake area growth, alongside a rising temperature trend (Islam & Patel, 2022). It has been reported that as the current trend of climate warming continues, further glacier melting is likely to occur which will have the adverse influence on regional warming on the hydrology of Sikkim Himalaya due to accelerated cryosphere thawing (Shukla et al., 2018). Research studies have suggested that the deposition of aerosol particles is closely associated with the intensification of glacier retreat (Kumari & Middey, 2023). In a recent long-term study (1990–2022) conducted in Sikkim, it has been concluded that CC is responsible for the alterations of the physical characteristics of the glaciers (Saha et al., 2024).

About two decades ago, altogether 84 glaciers covering an area of about 440 sq. km with the total extent of permanent snowfields being 251 sq. km in Sikkim have been reported(SAC, 2001). A significant rise in the rate of glacier retreat in the Sikkim Himalaya has been observed by scientists in recent times due to the effects of global CC (Bhutia & Gurung, 2019). The Sikkim Himalaya is vulnerable to climate GLOF induced by CC. Plate 5a, b show the before and after the impact of flashflood induced by GLOF of October 4, 2023, at Sirwani and Singtam, East Sikkim.

5 Possible Threats Due to CC in Sikkim

The Himalayas are warming more quickly than the rest of the world, as is often recognized. (Singh et al., 2010). As the effects of CC become more apparent, adaptation is becoming increasingly necessary. In the event of adaptation strategies not implemented successfully, temperature and precipitation variations will have detrimental effects on climate-dependent industries like agriculture, water resources, and health. Among these, agriculture is by far the most significant source of income for mountainous rural populations, and it is closely correlated with water supply and temperature. In a study conducted before, the South and West districts of Sikkim

Plate 5 (**a**) The lower elevation zone of Sirwani is vulnerable to the impact of GLOF -(13.06.2015). (**b**) The lower elevation zone of Singtam impacted by GLOF of 04.10.23

Plate 6 Drying spring source in Duga, East Sikkim (13.06.2015)

were determined to be the most vulnerable to CC-related changes, whereas the East and North districts were found to be reasonably resilient(Tambe et al., 2011). Sikkim has experienced unpredictable rainfall patterns, the disappearance of local springs and watercourses, species relocating to higher altitudes, the emergence of plant diseases and dangerous species that could jeopardize native species, and changes in the sowing and reaping phases of crops as a result of CC (Sharma & Rai, 2012).

In the days to come, the Sikkim Himalaya will face numerous challenges from the severe problem of CC, which has already been exposed to it. Water shortage could result from it, particularly in Sikkim's drought-prone regions like Duga, Namthang, and other areas of South Sikkim (Plate 6). Changes in rainfall patterns could lead to a decline in agricultural production and river hydrology would be negatively impacted by CC. Resultantly, the frequency of flood will be increasing because of heavy and unexpected rains. In addition, prolonged heavy downpour may result in landslides on a greater scale. In addition, changes in the hydrology of rivers would have a negative impact on biodiversity and aquatic habitats in addition to the current hydroelectric plants.

6 Conclusion

Sikkim has a long history of adopting sustainable development practices and has never shied away from taking the initiative to take all kinds of environmental protection measures. The goal has always been to increase the amount of green space and preserve the mountain state's delicate environment, whether through the Green Mission or the Organic Mission. Nonetheless, scientific data indicate that Sikkim Himalayas is experiencing the consequences of CC and globalization. However, the in-depth knowledge and data on the impact of CC on various taxa and different ecosystems in the Himalayan region are largely missing. In order to maintain the nation's natural resources, protect rural livelihoods, and promote sustainable development, CC adaptation strategies are crucial. Documentation of traditional knowledge, its revival, and strengthening for sustainable development and adaptations to CC should be made. It is important to promote the development of strategies on vulnerability and adaptation at all levels and to build capacity for integrating adaptation issues into sustainable development plans in various sectors that are vulnerable to CC. These strategies should be effective and outcome-based. Some of the existing policies and programs which are relevant in the contest of CC are State Green Mission, Water Recharge and Watershed Management Programme, 10 min to Earth Programme, *Paryavaran Mahotsav*, *Smriti Van*, *Mith/Mitini Tree*, *Mero Rukh Mero Santati*, Soil, and Water Conservation Initiatives, mechanization and promoting horticulture are particularly relevant. Parallel to this, public education on the preservation of biodiversity and the personal responsibility for reducing ecological footprints should be practiced. Lastly, any further developmental projects should be planned only after ensuring integration of environmental, economic, and social sustainability. There is an urgent need of setting up a high-level commission for suggesting preparatory strategies and mitigation policies considering the vulnerabilities of the Himalayan State to CC. With scientific planning and formulating correct strategies, the adverse impact of CC on different sectors can be mitigated.

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Climate Change and Natural Disasters: Navigating a Legal Response

Shivangi Vashishta and Vidhi Madaan Chadda

1 Introduction

Climate change is a direct consequence of fossil fuel intensive anthropogenic activities. The burning of fossil fuels to meet global energy demands led to the release of greenhouse gas emissions (GHGs) which trap the sun's heat and radiation leading to planetary warming. Global warming sets in motion a chain of events which lead to disbalance in the global ecosystems thus affecting the delicate balance that makes survival on Earth possible. One of the direct and most visible impacts of climate change is the impact on human activities due to the changing weather conditions, making sudden and slow-onset disasters more intensive and frequent. India is an economy which is highly dependent on natural resources and weather conditions as agriculture predominates among other economic activities. Its vulnerabilities are amplified because it is the second most populous country in the world. Therefore, not only mitigation, but adaptation to climate change also becomes extremely important considering the exposure it has to the impacts of climate change. Since climate change will lead to an increased risk of catastrophic events, it is key to evaluate the existing mechanisms of disaster risk reduction as well as management.

Climate change is described in Article 1 of the United Nations Framework Convention on Climate Change (UNFCCC) as a change in the climate, linked either directly or indirectly to human action that alters the chemical makeup of the world's atmosphere which is over and above the organic climatic change observed over comparable time periods (Bodansky, 1993). Hence, the UNFCCC differentiates between climatic fluctuation due to natural causes and climate change that can be attributed to human activities changing the composition of the atmosphere.

S. Vashishta
Indian Institute of Corporate Affairs, Haryana, India

V. M. Chadda (✉)
Faculty of Law, University of Delhi, Delhi, India

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Intergovernmental Panel on Climate Change (IPCC) stated in its fifth assessment report (FAR) that the climatic changes in the past decades have had a significant impact on both human and natural systems on every continent and in every ocean. Although for natural systems, there is more compelling and direct evidence of such impacts, human systems have also been impacted, with a substantial or little distinctive contribution of climate change along with other factors (IPCC, 2014a, b).

South Asia is one of the most vulnerable regions in the world to sudden-onset events (Ober, 2019). Consecutively the growing incidences and intensities of slow-onset disasters, particularly in the light of climate change, have now accorded them also, the much-needed attention (Kafle, 2017). India is a particularly vulnerable nation both in terms of sudden and slow-onset disasters as its diverse geography is characterized by a warm desert, cold desert, snow-clad mountain regions, 7756 km coastline, plateaus, plains, grasslands, evergreen forests areas, riverine, deltas, Sundarbans, and a number of islands. India covers 2.4% of the world's land area but houses 17.5% of the planet's population. It has the largest percentage of the world's poor (30%), an estimated 24% of the world's population without having electricity available (304 million), roughly 30% of the world's population using solid biomass for preparing food, and 92 million without safe drinking water (Patil, 2012). Therefore, in light of changing climatic conditions, the delicate balance of the existing ecosystem is set for an overhaul, which would increase the risk of communities dependent on these ecosystems wherein the aspect of risk reduction and mitigation becomes extremely significant (IPCC, 2014a, b). The process of disaster management has several aspects, covering from predisaster preparedness and risk mitigation, during the disaster rescue and relief, and postdisaster recovery and rehabilitation (Mohanan, 2016). The disaster management (DM) regime before 2005 was focused only on the postdisaster aspects (Kafle, 2017).

As the frequency and intensity of disasters increased, the concepts of preparation, risk reduction, and mitigation started garnering due attention (Shaw, 2009). Although all countries are indiscriminately subjected to natural disasters since time immemorial, however, it has been noted that the developing and least-developed countries have encountered the most loss and damage related to natural disasters (Kafle, 2017). The large population and lack of sensitization have been discerned as the possible causes of this situation. In order to further understand the nature of climate change-induced disasters (CCID), it is important to implore into the linkages between climate change, disaster risks, and loss and damage.

The study aims to examine the existing legal framework for climate change in India and analyze if it incorporates the important aspect of climate change-induced disaster risk management. The study also seeks to critically analyze the legal framework governing natural disasters, per se, in India for its adequacy to address climate change-induced disaster risk management.

2 Climate Change and Disaster Risks: Linkages

Climate change has been proven to be a threat multiplier (IPCC, 2014a, b), which means the vulnerabilities of already vulnerable sections of society will increase since these sections lack the capacity as well as means to cope with the impacts of climate change. According to the United Nations Disaster Risk Reduction (UNDRR), countries should adopt such disaster risk management which must be founded on knowledge of disaster risk in all its manifestations, including susceptibility, capability, exposure of people and property, hazard characteristics, and the environment. Such information may be applied to risk assessment, mitigation, prevention, readiness, and reaction. In least-developed and developing countries, there is an enhanced risk of weather-related hazards (Zorn, 2017). Climate change is expected to have a variety of effects that will increase the likelihood of disasters (Burton et al., 2002), but the exact effects are yet uncertain, and it is crucial to understand that not all locations will be affected equally (IPCC, 2014a, b). Certain events exemplifying the linkages between climate change and disaster risks are as follows (Ober, 2019):

- **Floods:** Floods are commonly defined as an overflow (Kakinuma et al., 2020) of water from water bodies beyond its normal geographical area on account of various causes like heavy rains, storms, or incessant melting of snow, which brutally impacts the areas in the vicinity causing loss and damage of life and property (Ibid.). In India, floods as well as the impacts of these disasters affect 23 states and UTs covering a geographical area of 45.64 million hectares. During the period 1996–2005, India faced a loss of INR 47.45 billion on account of floods. Scientific data has proven that daily rainfall incidences may become more intense by around 7% for every 1-degree Celsius increase in global temperatures (Allan et al., 2021). By 2100, coastal flooding caused by sea level rise will endanger assets valued at 20% of the global GDP (Kirezci et al., 2020).
- **Cyclones:** These are highly destructive and Indian coasts are especially vulnerable to its impacts (Venton & Trobe, 2008). Climate change is expected to amplify the frequency and intensity of tropical cyclones and related secondary impacts, like flooding, intrusion of salt water, and storm surges (Ibid.).
- **Droughts:** It is a slow-onset natural disaster wherein long spells of no rainfall cause an overall reduction in the food security of the area, thus impacting large-scale human lives and the biodiversity of the region (Cook et al., 2018). In its Fourth Assessment Report, IPCC stated that increased temperatures will lead to a greater number of droughts in middle latitude and partially arid regions, water stresses across the world, impacting millions of humans each year (Ibid.).
- **Avalanches:** High-confidence scientific data backed by IPCC reports highlights that glaciers are continuing to shrink almost everywhere as a result of climate change impacting runoff and water supplies downstream. Climate change is warming and affecting the permafrost in regions at high latitudinal and areas with high elevation (Geest et al., 2021). These changes along with other observed changes in rainfall or snow melt and ice affect hydrological systems locally as well as elsewhere, thus affecting the quality and quantity of water reserves

(Ibid.). This was particularly crucial for India because it is adjoining as well as downstream of the so-called third pole of the world, which makes it extremely vulnerable to avalanches.

- **Heatwave**: Heat stress from extreme heat and humidity could annually affect 1.2 billion people by 2100 (Hao & Singh, 2020). Adding to these major disaster risks, another concern is heat waves, as the fire season which is witnessed around the globe is projected to increase in its duration on account of climate change to three months in regions already prone to wildfires (Benthuysen et al., 2021).

Therefore, climate change risks form a subset of disaster risks, however determining the source of climate change as well as defining the scope of its future implications remains a challenge which was not the case for disaster risks that are not accounted for climate change, for example, earthquake, nuclear leak, etc.

2.1 Climate Change-Induced Loss and Damage and Disaster Management

Disaster generally means a destructive happening either on account of natural causes or human activities which lead to large-scale loss and damage. Since the so-called traditional natural disasters were a result of a localized natural event, the responsibility of extending relief was borne by the state wherein disaster has hit (Govind & Verchick, 2015). However, in light of the proven fact of increasing frequency and intensity of natural disasters on account of climate change, the onus of supplementing the adaptive capacity of vulnerable communities and bearing the loss and damage associated with such disasters is put on the countries that have benefited from the increased release of GHG emissions (Boyd et al., 2017). It is imperative to highlight that the responsibility for the management of disaster, no matter caused by climate change, will primarily rest with the state wherein disaster has hit, no matter whether the state shall demand redemption from the GHG emissions emitting state (Govind & Verchick, 2015).

The concept of loss and damage has been categorized as one involving irreversible harm, for instance, loss of land area on account of the rise in sea level and the other incurring damage which can be repaired or recovered though at a cost, such as impacted infrastructure (Morrissey & Oliver-Smith, 2013). Another point of distinction is based on the nature of loss and damage which includes economic and noneconomic L&D, as well as slow-onset and severe storms (Doelle & Seck, 2020). Though it is easier to evaluate economic loss and damage like the value of lost assets, however, measuring noneconomic assets like cultural heritage, etc., is difficult to ascertain (Serdeczny, 2019). Therefore, the focus of efforts tackling climate change shifts to averting the loss and damage altogether.

Building resilience is one such approach to tackling climate change-induced disasters which has been defined by IPCC as the ability of societal, economic, and ecological aspects to respond to or reorganize in response to a risky event, trend, or disruption while retaining their ability to adapt, learn, and transform (Doorn, 2017).

It can be said that the majority of the adaptation efforts seek to reinforce the capability and resilience of the communities in the light of impacts of climate change becoming more apparent (Yamin et al., 2005). The Adaptation and Loss and Damage Fund agreed to be set up under the aegis of UNFCCC at the COP27 in Sharm-El Sheikh, Egypt aims to provide aid to climate-induced disaster hit least-developed and developing countries, primarily funded by the developed country (Alayza et al., 2022). Although loss and damage are mentioned in the Paris Agreement of 2015 (UNFCCC, Paris agreement, 2015), but with the trajectory of nations' aggregate nationally determined contributions (NDCs) cumulatively progressing to locking the world into 3 °C or greater warming and making the probability of increasingly frequent and severe climate losses and damages inevitable, the need for climate change-induced disaster risk management will remain key.

2.2 Need for Mainstreaming Climate Change Risk Management

Stability and predictability are keys to the progress of an economy. Disaster or a catastrophic event causes disturbance in the economic activity as well as loss of key assets in the area. Therefore, disaster management law and policy have emphasized the need to mainstream disaster risk management in the development plans of the countries (Mal et al., 2018). With the risk and uncertainty of catastrophic events increasing on account of climate change, it becomes important to evaluate and inculcate the aspect of climate risk in the development policy, laws, and plans.

The global experience stands witness to the fact that disasters are followed by the displacement of affected people. Almost 18.8 million individuals were forced to leave their homes due to sudden disasters in 2017, with 11.4 million (approximately 60%) of those people living in South and East Asia (Kafle, 2017). According to the World Bank, due to water scarcity, crop failure, sea level rise, and storm surges, there will be roughly 140 million internal climate migrants by 2050, 60 million of whom will live in South Asia alone (Anwar, 2021). Such migration is mostly unplanned and takes a toll on human life while it also disturbs the already stressed natural and human systems in the areas they migrate to. Therefore, a disaster impacts the health of human beings (Makwana, 2019) occupying the area where the disaster hits, the infrastructure (Choi et al., 2019) in place to supplement their domestic and economic activity, the environmental resources (Smith, 2013) as well as their capabilities to survive, earn a livelihood, and develop altogether (Jones et al., 2010).

In order to prevent, reduce, and deal with losses and damages, it is emergent to develop and put into practice effective approaches for managing climate risk which are backed by scientific proof and climate policy negotiations as there is a growing awareness of a global scale that mitigation and adaptation efforts might not be adequate for controlling the consequences of climate change (Roger et al., 2022). The IPCC Special Report on Extreme Events has recognized the development of a Climate Risk Management framework for thoroughly lowering, planning for, and funding climate-related threats while trying to address the associated risk drivers, such as climate-related and socioeconomic variables (IPCC, 2014a, b). The National Disaster Management Institute (NDMI) has postulated a climate risk management framework wherein the various risk management measures are to be taken while accounting for the risk posed by climate change considering the potential, perceived and probable challenges to adaption and capacity building processes (Mechler et al., 2019). Policy awareness of climate risks exists in India but a pressing need has arisen to create a solid Climate Risk Management framework that could be used to guide decision-making in addressing both the climate vulnerability and disaster risk challenges as well as supplement climate change proof capacity building (Ibid.).

3 Framework Governing Climate Change-Induced Disasters in India

At the inception of the twenty-first century, governance of disaster management had seen a paradigm shift from being response and relief-centric to becoming mitigation and preparedness-oriented, in line with the recommendation of the United Nations-International Decade for Natural Disaster Reduction (UN-IDNDR) (Steffen, 1998). Presently, climate change awareness and sustainability concerns in DM are driving a second paradigm shift (Mechler et al., 2019). In order to fully evaluate the entire domain of law and policy framework governing climate change-induced disasters, an analysis is undertaken of the climate change regime for its postulation related to DRR and DM for risk and loss and damage due to climate change.

3.1 Legal Framework Governing Climate Change in India

The legal framework governing climate change is primarily based on international commitments of India on global platforms like UNFCCC, and under the mandate of Article 51(c), the same becomes necessary to abide by and respect in the light of the principle of good faith (Alexander, 1952). However, India has implemented a National Action Plan on Climate Change (NAPCC), Nationally Determined Contributions, etc. as part of its obligations under international climate governance. The framework is discussed as follows:

3.1.1 International Framework

The global community, sensitized by the scientific community about the fact of climate change (Houghton et al., 1992), established the UNFCCC in 1992 to drive action to combat the same. It is operated by the Conference of Parties (COP) which meets annually at different places around the world. Although it deals comprehensively with all aspects of climate change, from mitigation to adaptation, technology transfer, and financial aid among others. However, its emphasis on climate-induced disaster risk reduction per se has not been as would have been expected because such disasters are already being witnessed in some parts of the world. Kyoto Protocol to UNFCCC adopted in 1997, was a major intervention to combat climate change (UNFCCC, 1997); however, its primary focus remained mitigation while adaptation to climate change was included in the agenda of the UNFCCC only post Bali Action Plan (Verheyen & Roderick, 2008). Although the disaster word doesn't find mention in the Paris Agreement, the various Sustainable Development Goals (SDGs) (Hák et al., 2016) cater to various aspects of climate change-induced disasters (Kelman, 2017). SDG 1.5 especially gives a target of 2030 to mitigate the risk posed to the comparatively poorer sections of society on account of climate-related catastrophic events and the need to build resilience. Goal 3.d deals with the importance of early warning mechanisms, risk management, and the need for capacity building especially among developing nations. SDG 11.5 puts the target of 2030 to considerably reduce the mortality and other harms to people's health as well as economic losses related to disasters, especially focusing on hydrological extreme events. SDG 11.6 directly calls for the planning of cities and infrastructural activities to be in line with the Sendai Framework for Disaster Risk Reduction (SFDDR) 2015–2030, which requires the implementation of holistic multilevel disaster risk management. SDG 13.1 required the building of capacity and resilience in all communities for handling CCID and hazards especially focusing on women and other marginalized sections of society, whereas goal 13.2 required the development of national plans and policies with consideration of climate change. Lastly SDG15.3 requires the countries to make efforts toward combating desertification, and restoration of degraded land and soil, including drought-stricken and floods-impacted lands by the year 2030.

There has been progress in the aspect of loss and damage. The Warsaw International Mechanism for Loss and Damage (Serdeczny, 2019) adopted at UNFCCC COP 18, gives due importance to escaping, mitigating, and accounting for loss and damage related to the negative effects of climate change, including extreme weather events and slow-onset events. There exist points of commonalities among the solutions tools agreed upon by the Paris Agreement and the Sendai Framework of DRR which include robust risk evaluation, risk insurance mechanisms, and pooling of climate change-related risk.

3.1.2 National Framework

The Constitutional provisions under Article 21 extend the Right to Life, Health, and Clean Environment to the citizens of India which entails that the state shall protect these rights from possible infringement. The fact of climate change poses a risk to all the three fundamental rights guaranteed by the Constitution of India (CoI), wherein life, health, and the environment are at risk of being negatively impacted.

The National Action Plan on Climate Change (NAPCC) provides the domestic framework governing climate change (Pandve, 2009). Currently, NAPCC is implemented through eight National Missions, outlining priorities for mitigation and adaptation to combat climate change (Ibid), with the GOI planning to add four more missions focusing on linking climate change with health and coastal areas among others (Sorokhaibam & Shrivastava, 2021). Only a few missions focus on building resilience as majorly the focus of the plan is on mitigation. National Mission for Sustaining the Himalayan Ecosystem is one such mission which aspires to curtail the melting of glaciers (Pandve, 2009). Mission on Sustainable Agriculture is also adaptation-oriented as it seeks to develop and increase usage of climate change-resilient crops and the ambit of weather insurance. Under the Ministry of Health and Family Welfare, which is the nodal ministry for health mission, the National Center for Disease Control (NCDC) has been assigned as a technical nodal body for implementing the mission which drafted the National Action Plan for Climate Change and Human Health (NAPCCHH) in 2018. Therefore, some aspects of capacity building and security of life are being addressed by the missions.

Along with NAPCC, the subnational states of India have enforced their State Action Plan on Climate Change (SAPCC) with an intention to mainstream the impacts of climate change in their development plans (Ibid.). The NAPCC has a diverse focus, but it fails to mention the risk from climate-induced disasters even once which highlight that the plan does not factor in such a possibility which needs to be prepared for. The Nationally Determined Contributions (NDCs) to UNFCCC by India quote PM linking climate justice with the need for preparing for the risks posed by natural disasters. The focus of the regime is primarily mitigation of climate change by reducing emissions intensity while adaptation to climate change which includes disaster risk mitigation has not been given much focus. A National Adaptation Fund for Climate Change (NAFCC) has been created to supplement adaptation measures in those states and union-controlled territories (UTs) in India that are vulnerable to the impacts of climate change.

Other ancillary laws like the Environmental Protection Act 1986, Air (prevention and control of pollution) Act, 1981 (Sharan & Gupta, 2019), and Water (prevention and control of pollution) Act 1974, have also been invoked to hold accountability for polluting activities in line with the polluter pays principle which ultimately contributes to climate change, and the same has been curtailed by the Supreme Court on account of their such potential of adding to the menace of climate change (Gagrani, 2022).

3.2 Legal Framework Governing Disaster Management in India

The DM framework in India is also backed by International framework and holds significance in the light of Article 51(c) of the CoI which requires the state to respect the treaties and conventions agreed to by the government on behalf of India. Domestically, the DM framework is fourfold with the DM law, policy, plan, and guidelines forming its four constituents (Pandey, 2016).

3.2.1 International Framework

The United Nations celebrated the IDNDR in 1994 which became an important international initiative, heralding a series of constructive collective actions in the field of DM. It necessarily brought the attention of the world to the need for managing disasters (Aitsi-Selmi Amina et al., 2015). It was succeeded by the International Strategy for Disaster Reduction of 1999. The Yokohama Strategy of 1994 for DM was also adopted on the lines of IDNDR which were followed by the Hyogo Framework for Action (HFA, 2005), and most recently the Sendai Framework. The COP session agreements and adoption of Millennium Development Goals took place simultaneously with the HFA process (Ibid.). The three policy instruments had potential synergies as all three were science-based with implications on human life and health; however, the same potential was not realized (Ibid.). As part of the HFA text, Governments consent to mainstream climate change adaptation and DRR in their development plans through the identification of climate change-induced disaster risks, framing of DRR targets, and regular use of climate risk data by key nonstate stakeholders, science experts, and other decision-makers (Aitsi-Selmi Amina et al., 2015).

The SFDRR which was adopted at the third edition of UN WCDRR in March 2015 in Sendai, Japan for a period of 15 years, has science and risk-based decision-making at its core (Carabine, 2015). It requires under provision 33(a) the countries to draft and regularly update their inclusive plans for disaster readiness and emergency with the participation of all relevant parties while considering the fact of climate change and its impact on disaster risks altogether. The representatives of almost all the nations in the world recognized the increasing frequency of disasters and the need to mainstream DM into national development plans and planning processes.

3.3 National Legal Framework

The Disaster Management Act, 2005 (hereinafter referred to as DM Act) is a comprehensive legislation enacted by the Government of India (GOI) to establish a comprehensive executive framework governing disaster management. The act has aimed to assimilate disaster risk considerations into various developmental plans. The term Disaster has been defined in the act under Section 3 (d), as a calamity, adverse event, catastrophe, or grave incidence in any area, arising from natural or man-made causes, or by accident or negligence, which results in significant loss of life or human suffering, or harm to, and damage of, property, or injury to, or deterioration of, the environment, and is of such a nature or severity that it surpasses the coping capacity of the impacted population. Whereas section 3 (e) of the Act defines DM as an ongoing and assimilated process of planning, preparing, coordinating, and implementing measures that are necessary or expedient for preventing the danger or threat of any disaster; mitigating or reducing the risk of any disaster or its severity or implications of capacity building; preparedness to deal with any disaster; respond promptly to any threatening disaster situation or disaster; assessing the severity of any disaster. Therefore, definitions of both disaster and DM can be interpreted to include climate change-induced disaster and climate change-induced disaster management as they include within their scope the aspect of natural and man-made causes of disasters, providing a significant loss of human lives or harm to property can be attributed to such disasters as well as seeks to prevent and reduce the threat of such disasters altogether (Ibid.). The National Disaster Management

Authority and the state DM authorities established under the act are responsible for executing and achieving disaster preparedness as well as risk reduction in respective demarcated jurisdiction. The act provides for the DM Division of the Ministry of Home Affairs to retain the overall command of the national disaster response. Ideally, a synergy in the functioning of these authorities established by the act is required as per the act. The act also takes into account the factors of providing relief in the face of disasters ranging from the provision of water to concessions in getting loans and loan repayments.

As per Chaps. III and IV of the Act, the executive framework for state- and district-level DM has been respectively laid out. Section 35 is an enabling provision, which empowers the Central Government to necessarily take and ensure all such measures are taken as it deems appropriate and imperative for successful DM, subject to other provisions of the act. It ranges from ensuring coordination with national and international state actors, finance, establishing institutions for research, and other actions needed to ease implementation of the act.

Section 64 of the DM Act allows for the national executive committee and its state and district counterparts to draft or amend rules, guidelines, notifications, bylaws, etc., in the light of the existence of certain circumstances which require such addition or amendment for preparing or mitigating any disaster risk, climate change-induced disaster. Provision for the creation of a fund with the name of National Disaster Mitigation Fund for purposes of mitigation of disaster risks is to be given under the DM Act. Therefore, it is prudent to conclude that the DM Act can be interpreted to include within its scope climate change-induced disaster.

The National Disaster Management Policy identifies climate change as a risk enhancer along with population growth, rapid unplanned urbanization, carbon-emissions-intensive industrialization, developmental activities in ecologically sensitive areas, and environmental degradation (Das, 2012). The policy also has a separate theme titled climate change adaptation wherein clause 5.1.7 states that India's glacier reserves, water balance, agriculture, forestry, coastal ecology, biodiversity, and human and animal health are all being impacted by climate change (Ibid.).

It has been shown that in the upcoming years, climate change will make natural catastrophes like cyclones, floods, and droughts more frequent and intense. In this light, the policy identifies the potential to form synergies between the policies for disaster risk reduction and climate change adaptation which if supported and fostered has the potential to successfully address these challenges. It also calls for more dedicated research in the area of climate change and planetary warming especially in the context of India to be conducted by a core group of scientific experts working in the area of disaster risk reduction. With respect to the theme of forest fires, it holds the Forest Protection Division as the nodal authority for matters pertaining to DM which is primarily responsible for implementing central government's Forest Fire Prevention & Management Scheme (hereinafter referred to as FPM).

Additionally, in adherence to the policy narrative, the National Database for Emergency Management (NDEM) and National Spatial Data Infrastructure (NSDI) are based on Geographic Information System (GIS) databases for hazard zoning, exposure analysis, and hazard-implications mapping (Navalgund Ranganath et al., 2007). Therefore, the policy covers various key aspects of disaster risk mitigation, preparedness, response, and recovery.

National Disaster Management Plan, 2019 has been instituted taking into account climate risk while devising a strategy to manage disasters. It broadly has six themes (Ogra, 2022). The first theme highlights the importance of risk assessment. Second theme holds coordination among stakeholders as key for DRR (Ibid.). The next two themes require DRR measures focusing firstly on physical structure which can help a community cope with disasters and secondly, on legal framework and techno-legal interventions. Climate change risk management theme highlights how climate change impacts may increase the incidence of severe weather; however, there is no particular objective that can be accomplished under this theme. It does mention remaining mindful of data gaps when assessing the effects of climate change and keeping in mind the time frames in which climate situations are generated and DRR operates (Ibid.). The plan recognizes the scope of synergies between sustainable development and climate risk reduction.

Lastly, the national DM guidelines for the preparation of state DM plans, 2007 use the term climate change once while identifying it as one of the factors contributing to disaster risks. Several hazard-specific guidelines have been released by the NDMA. The guidelines for drought, avalanches, and landslides take into account climate change; however, guidelines for flood released in 2008 do not take into consideration climate change. Guidelines for the preparation of an action plan on heat waves released in 2019, have no mention of climate change. Guidelines for disability-inclusive disaster management also omit the consideration of climate change. Strikingly, the guidelines issued for cyclones in 2008 include climate change considerations. Therefore, there is a lack of uniformity and standardization in the state's approach to DM. It is crucial in the face of climate change, that the guidelines and every piece of legislation for that matter reflect the seriousness of the situation the world is stepping into.

Some ancillary measures have also been taken to further DM in India. The Ministry of Environment, Forest, & Climate Change (MoEFCC) has identified a Hazard Line mapping the territorial coast of India under the aegis of the Integrated Coastal Zone Management (ICZM) project (P.I.B., 2022), while efforts are being directed toward the conservation and preservation of the sensitive coastal and marine environment on the principles of sustainable development (Coastal Regulation Zone Notification, 2019).

4 Identification of Gaps in the Legal Framework and the Role of the Indian Judiciary

UN International Strategy for Disaster Reduction (UNISDR) in its report stated that the evidence of the efficacy of existing risk governance framework to adequately mitigate underlying risk factors is very scant (Zhongming et al., 2013). It is to be seen how the already questionable framework handles the novel risk posed by the uncertain impacts of changing climatic conditions on the planet. Since 2005, India has evolved a robust framework to manage risk posed by disasters but implementation of the act remains key for any legislation to achieve its set purpose. Some of the major factors have been highlighted below:

- **Administrative Lacunas:** The implementation of existing laws and policies governing DM is riddled with the problems of lack of political intent and will (Ogra, 2022), highly distributed decision-making authority (Ibid.), a lack of an innovative techno-legal system (Ghosh, 2013), a lack of capacity building and sensitization of ordinary citizens (Shah, 2011), a lack of risk evaluation and information dissemination, a lack of area and context-specific data and examples, and an absence of an objective and standardized extreme events database. These issues not only lead to a lack of adequate disaster risk management but also amplify even the manageable risk of most vulnerable sections of society, in the light of the effects of changing climate.
- **Restricted in Scope:** It is noted that the frameworks governing climate change and disaster management in India are restricted in its scope as they do not account for the differences in physical and sociocultural realities of the people. Though gender has been included as a differentiating factor in the DM plan and NAPCC, the same has not been given its full operation due to a lack of the gender-transformative approach which has been widely accepted to aid capacity building as well as seeking gender empowerment per se (Ariyabandu, 2005). Also, the scope of the act is restricted with respect to a lack of special provisions for persons with disability as well as with special needs, which in light of climate change will lead to disproportionately increased risks for these sections of individuals. However, provisions for marginalized sections have been included in the NDMP, but no action has been taken in this regard.
- **Need for Mainstreaming Climate Change in Disaster Law & Policy Framework**It is suggested that there is a need to integrate the risk from the impacts of climate change into more board efforts to mitigate risks on account of all types of natural disasters (Van & Maarten, 2006). However, it is important to highlight that the data on the impact of climate change remains inconclusive which impedes the process of pinning accountability for loss and damage arising because of the activities causing climate change. Therefore, the aforementioned evaluation of the legal framework and the gaps highlights the insufficiency of the current legal regime to account for the climate change-induced disaster impacts in comparison to the robust international framework.

The law and policy lack the acknowledgment of the fact that climate change is a phenomenon with inherent differences from the governance of so-called traditional disasters due to its causal linkages being transnational as well as its cause of impacts being highly uncertain as per the existing scientific knowledge. Such risks require recognition and inclusion in the legal framework as well (Upmanu & Lall, 2019). Also, the nature of such impacts across different sectors of the economy requires the adoption of sectoral DM plans in addition to the existing ministry-specific plans (Hodam et al., 2022).

The basic framework of CoI is built on the principle of separation of power. In adherence to the principle of separation of power, it is incumbent on the three pillars of governance to keep a check on each other in terms of the fulfillment of the mandate given by the CoI. In such an event, if the legislature fails to put in place adequate legislation to address the subject area at hand and the executive fails to implement the existing legal framework to achieve the desired results required to address the situation, then the role of the honorable Judiciary becomes of extreme importance.

The Supreme Court under Ar. 32, which is the fundamental right to constitutional remedies, and Ar.136, which is the power of the Supreme Court to grant special leave to appeal, can use its jurisdiction to provide appropriate relief under the subject matter at hand. The infringement of the aforementioned Fundamental Rights on account of climate change-induced disaster can be addressed by the Supreme Court under the provisions of Ar. 32.

As the Indian judiciary has played a pragmatic role in developing the environmental jurisprudence in India, by applying the general principles of International Environmental Law like the polluter pays principle, precautionary principle, sustainable development, and now, the environmental rule of law, it becomes incumbent on the Judiciary to redress the rising need for accountability for lack of necessary climate action on account of adaptation capacity building, and other risk mitigation measures in the event of the absence of a robust climate change-induced disaster risk management legal framework. The right to a safe environment can be enforced by general legal innovation on account of the Judiciary, and precautionary principle per se.

Since the legal action in India in terms of claiming the lack of a mechanism to implement climate change-induced disaster risk management and seek redress thereof is largely missing except for the enforcement of specific environmental mandates, some instances of international climate change litigation have been taken up.

In two cases before the European Court of Human Rights (ECHR), Duarte Agostinho v Portugal (Duarte Agostinho and Others v Portugal and Others, 2020) and Greenpeace Nordic and Others vs. Norway (Greenpeace Nordic and Others v Norway, 2021), petitioners held 33 countries responsible for the climate change which have a potential to infringe their human rights guaranteed under ECHR, i.e., right to life under Article 2 and right to health and domestic life under Article 8 (Mohan et al., 2022). They allege that due to a lack of mitigation measures, their health, domestic life, and privacy will be impacted and on account of the rising risks of future possible damage, action must be taken to mitigate such risks to fundamental rights in consonance with the principle of intergenerational equity and the precautionary principle. The challenges faced in such litigations internationally as been threefold:

- The petitioners faced challenges in establishing the locus standi, specifically when it came to the aspect of the domestic remedies not yet exhausted, which is the stand of the Indian Judiciary as well when dealing with litigation demanding climate change law (Peel & Osofsky, 2015).
- The fact of absence of a clear cause-and-effect linkage between governmental inaction with a risk of future infringement of fundamental or human rights (Heri, 2022).
- Lastly, the challenge to extend the application of these rights beyond the territorial jurisdictions.

In 1995, the Supreme Court, gave due recognition to the principle of Intergenerational Equity (IGE) when it restricted the establishment of new wood entities without appropriate environmental due diligence. The aforementioned issue of locus standi is redressed in India by the introduction of the concept of Public Interest Litigation by the Indian Judiciary. (Bandhua Mukti Morcha vs. Union of India, 1984). Additionally, the honorable court has accepted the locus standi of the petitioners in the context of principle of IGE. The basis of such rulings is the Constitutional guarantee of the FR to life, health, and clean and safe environment. On the aspect of a causal relationship, it is noted that the majority of the environment and climate litigation in India has primarily entailed seeking specific relief from the judiciary (Hanuman Laxman Aroskar vs. Union of India, 2019). The present research took into account three SC cases which dealt with disaster management primarily, but all had only a reference or mention of climate change as a factor adding to existing disaster risks. Lastly, for cases related to environmental degradation, the SC has generally applied the precautionary principle to avoid future infringement of human rights in the light of possible negative impacts of climate change as the principle allows the judiciary to take the requisite action even when the basis of the claim of infringement has not been entirely proven. Therefore, judicial activism has proven beneficial for the interest of the environment and natural justice per se, and the same approach of the judiciary can be seen to develop while dealing with climate change litigation as well, while also noting that the judiciary has categorically refused to entertain a petition for evolving the climate change law.

5 Conclusion

In the recent past, India has exhibited its commitment toward tackling climate change and few of such aspirations have seen the light of the day as well. The promises made at the international platforms have made way for a legal framework at the domestic level; however, it has not led to a culmination owing to gaps in implementation. The present paper aimed at analyzing the regimes for climate change and disaster management in India for their adequacy in addressing the risk posed due to climate change-induced disasters. It is understood that the existing legal framework on disaster management in India must accommodate the risks emanating from climate change. It is further noted that coordinated and continued synergies between the three organs of the government can significantly reduce climate change risk provided they seek to mainstream climate change.

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Evaluation of Emerging Contaminants (ECs) in Water Resources, Spatio-Temporal Assessment, and Environment-Friendly Remedies: An Indian Perspective

Monica Gangopadhyay, Suman Naithani, Gaurav Singh, Pratibha Naithani, and Rachan Karmakar

1 Introduction

The river initially possesses clean water, but as it flows through urban areas, it becomes increasingly polluted. The rise in population density leads to a higher concentration of newly discovered pollutants. Over the past few decades, numerous new molecules have been detected in aquatic environments, categorized as either entirely human-made or naturally occurring compounds. This has raised concerns about the overall ecological impact and the availability of water resources. Most of these pollutants exist in nature as organic matter, typically in small quantities, and are known as emerging contaminants (ECs) (Smital & Barcelo, 2008). This type of contaminant encompasses both synthetic and innate compounds, in addition to pathogens, which are not commonly located inside the surroundings but have the capacity to pose dangers to human fitness and the ecosystem (USGS). These emerging contaminants represent a diverse group of micro-pollutants extensively studied in various water resources over the past few years. Figure 1. shows distinctive classes of ECs observed in Indian water sources.

It is essential to acknowledge that the majority of these emerging contaminants are not entirely novel or recently introduced to the environment; rather, they are substances previously recognized but now identified to have detrimental effects or specific modes of action. Therefore, the term "emerging" encompasses both the

M. Gangopadhyay · S. Naithani (✉) · P. Naithani · R. Karmakar
Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India
e-mail: suman_geu_naithani@geu.ac.in

G. Singh
Department of Civil Engineering, (Graphic Era Deemed to be University), Dehradun, India

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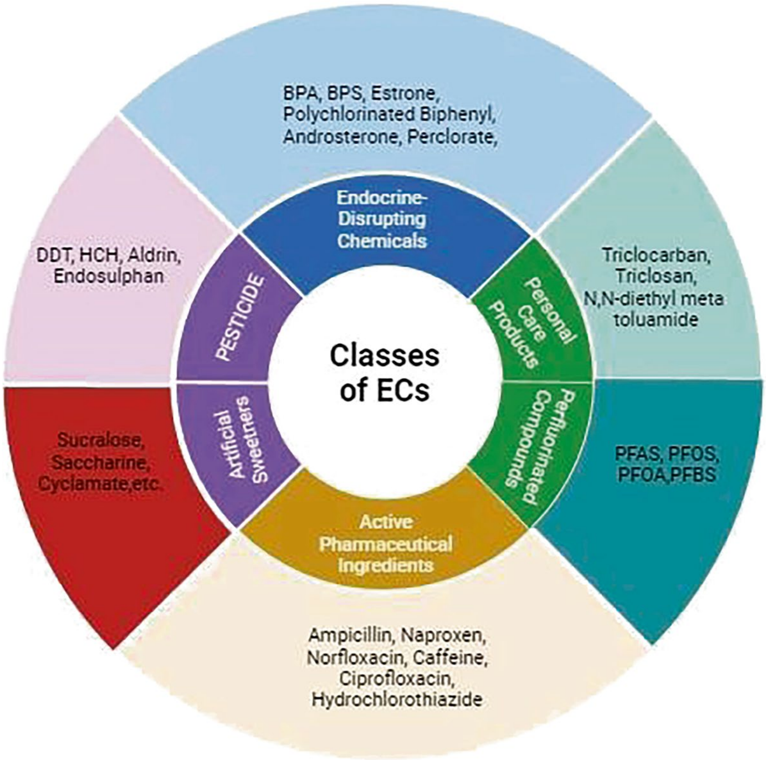


Fig. 1 Different classes of ECs found in Indian water resources and their Status of Emerging Contaminants in Water Resources

contamination itself and the increasing concern it raises as a problem (Rosenfeld & Feng, 2011). A variety of chemical pollutants, such as pharmaceuticals, hormones, insecticides, illegal drugs, X-ray contrast media, artificial sweeteners, cosmetics, personal hygiene items, UV filters, disinfection byproducts, and other industrial chemicals, have been detected in both surface and groundwater through recent research (see Table 1). These pollutants have been found in concentrations ranging from parts per trillion (ppt) to parts per million (ppm) (Aga, 2007; Barnes et al., 2008; Cabeza et al., 2012; da Silva et al., 2011; Fürhacker, 2008; Gao et al., 2014; Godfrey et al., 2007; Keerthanan et al., 2021; Khan et al., 2021; Loos et al., 2009; Lopez-Serna et al., 2013; Meffe et al., 2014; P'erez et al., 2011; Riva et al., 2018; Rout et al., 2021; Swartz et al., 2006; Teijon et al., 2010; Tijani et al., 2013; Valcarcel et al., 2011). Once introduced into the environment via septic tanks and defective sewage pipes, these substances traverse wastewater treatment plants, infiltrate groundwater, and ultimately reach rivers (see Fig. 2).

Table 1 The trend of Emerging Contaminants (ECs) in different Indian water resources

Location	Matrix	Contaminants
Uttarakhand, Uttar Pradesh	Surface water	Pharmaceuticals and drugs, PFASs, and EDCs
Uttarakhand, Uttar Pradesh, Punjab	Groundwater	
Himachal Pradesh, Uttarakhand, Uttar Pradesh, Delhi	Wastewater	
Delhi	Effluent	
Haridwar	Sludge	
New Delhi	Drinking water	
Hyderabad	Effluent	Pharmaceuticals and drugs, PCPs, EDCs, PFASs, and Flame retardant (TCPP)
Tamil Nadu, Telangana	Surface water	
Telangana,	Groundwater	
Coimbatore, Chennai	Wastewater	
Coimbatore, Karnataka, Tamil Nadu, Telangana	Effluent	
Tamil Nadu	Seawater	
West Bengal, Patna	Surface water	Pharmaceuticals and drugs, PFASs, PCPs, and ASWs
Patna	Effluent	
Patna	Wastewater	
West Bengal, Patna	Groundwater	
Guwahati	Surface water	EDC
Goa, Maharashtra	Surface water	Pharmaceuticals and drugs, PFASs, EDCs, and PCPs
Goa, Surat and Nagpur	Wastewater	
Goa	Seawater	
Nagpur	Effluent	
Ujjain	Hospital effluent	Antibiotic
Madhya Pradesh	PETL effluent	

2 Study Area

2.1 Indian Water Resources

India is blessed with abundant water resources, constituting approximately 4% of the world's total water. The rivers of India have been instrumental in the nation's development and are integral to its cultural heritage. Among the multitude of rivers, 12 are designated as major rivers, encompassing a catchment area of about 253 million hectares, while 46 are classified as medium rivers, covering 24.6 million hectares. These river systems exhibit varying flow patterns, with some flowing perennially while others are seasonal. The Ganga-Brahmaputra-Meghna system stands as India's largest, accounting for 43% of the catchment area of all major river systems. Other significant river systems include the Indus, Sabarmati, Mahi,

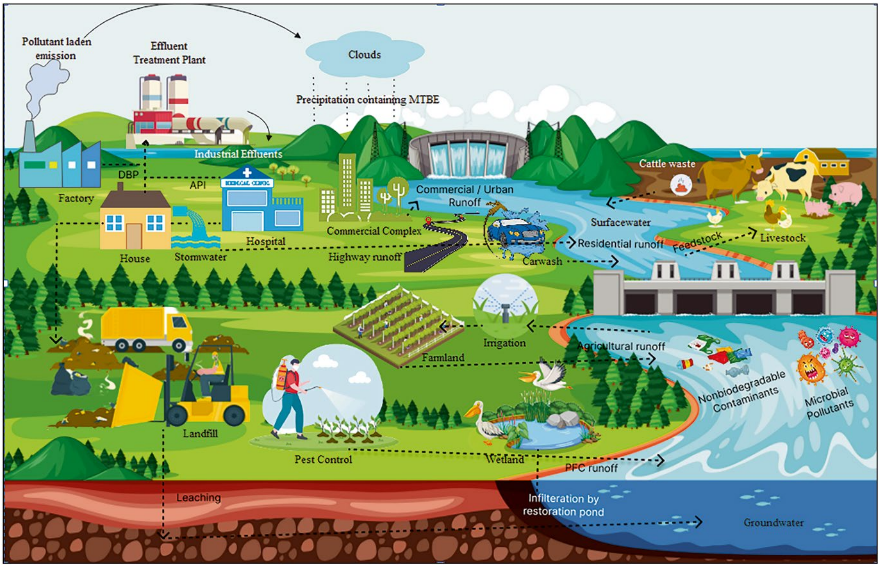


Fig. 2 Mobility of Different Emerging Contaminants in water matrices

Narmada, Tapi, Brahmani, Mahanadi, Godavari, Krishna, Pennar, and Cauvery rivers. Additionally, numerous medium-sized river systems contribute to the country's hydrology. Notably, the Subarnarekha river stands out for its expansive catchment area of 1.9 million hectares.

India boasts a diverse array of water resources beyond its rivers and canals. These encompass reservoirs, tanks, ponds, beels, oxbow lakes, derelict water, and brackish water, covering approximately seven million hectares. However, the distribution of these resources is uneven across the nation, with states like Orissa, Andhra Pradesh, Gujarat, Karnataka, and West Bengal collectively harboring over 50% of the inland water resources (Central Water Commission, 2015; Dhawan, 2017).

2.1.1 Northern Zone of India

In North India, researchers like Sharma et al., 2016; Mutiyar et al., 2012a, b; Mutiyar & Mittal, 2014; Yeung et al., 2009; Jindal et al., 2015; Singh et al., 2014; Gani et al., 2016; Mutiyar & Mittal, 2013 and Das et al., 2014 highlighted the contamination of PFAS (Per-and polyfluoroalkyl substance), EDC (endocrine disrupting chemicals), and PPCPs (Pharmaceuticals and Personal Care Products) in different water matrices (Table 1).

2.1.2 Southern Zone of India

Water pollutants such as pharmaceuticals, drugs, personal care products (PCPs), endocrine-disrupting chemicals (EDCs), per-and polyfluoroalkyl substances (PFASs), and flame retardant (TCPP) have been the subject of investigation in the southern part of India. Studies conducted by Larsson et al. (2007), Fick et al. (2009), Yeung et al. (2009), Archana et al. (2016), Rao et al. (2008), Ramaswamy et al. (2011), Kamaraj et al. (2013), Shanmugam et al. (2014), Rayaroth et al. (2015), Subedi et al. (2015), Sunantha and Vasudevan (2016), Rutgersson et al. (2014), Gani et al. (2016), and Anumol et al. (2016) have investigated the presence and impact of these pollutants (see Table 1).

2.1.3 Eastern Zone of India

Apart from contemporary pollutants such as drugs, per-and polyfluoroalkyl substances (PFASs), and personal care products (PCPs), the presence of amorphous solid waste (ASWs) in the eastern part of India has been evaluated by Yeung et al. (2009), Sharma et al. (2016), Subedi et al. (2015), and Roy and Kalita (2011) (see Table 1).

2.1.4 Western Zone of India

Several emerging contaminants and antibiotics were observed by Diwan et al., 2009; Diwan et al., 2010; Larsson et al., 2007 and Fick et al., 2009 in western part of the country (Table 1).

3 Materials and Methods

3.1 Water Quality Assessment

Evaluating the quality of water before its utilization for various purposes holds paramount importance. A comprehensive examination of water quality involves assessing a spectrum of physicochemical parameters. Physical attributes necessitate scrutiny through specific tests including temperature, pH level, electrical conductivity (EC), nitrate, sulfate, fluoride, among others. Moreover, chemical tests are essential to ascertain biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen content, and other pertinent characteristics.

3.1.1 pH

Measuring the acidic and basic properties of a water sample is crucially done through pH assessment, a critical factor in determining waterway health. Extreme pH levels, whether very low or very high, can significantly impact water resource biodiversity. Aquatic organisms possess remarkable adaptability to specific pH levels, with even slight deviations potentially leading to their demise. Acidic water, characterized by low pH values, exacerbates the toxicity of certain chemicals and metals upon interaction. For instance, fish accustomed to pH levels as low as 4.8 may succumb at pH 5.5 if exposed to just 0.9 mg/L of iron in the water. The introduction of acidic water containing aluminum, lead, or mercury can result in gill buildup in fish or deformities in young fish, diminishing their chances of survival. Figure 3 illustrates the spatiotemporal distribution of pH in Indian water resources.

In 2019, the highest pH levels were observed in Jammu and Kashmir, while the lowest were recorded in Kerala. Additionally, states such as Haryana, Himachal

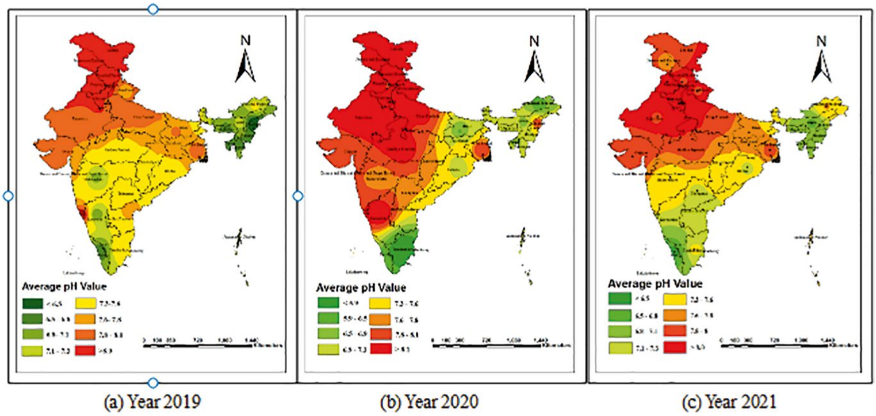


Fig. 3 Spatiotemporal distribution of pH in Indian Water Resources

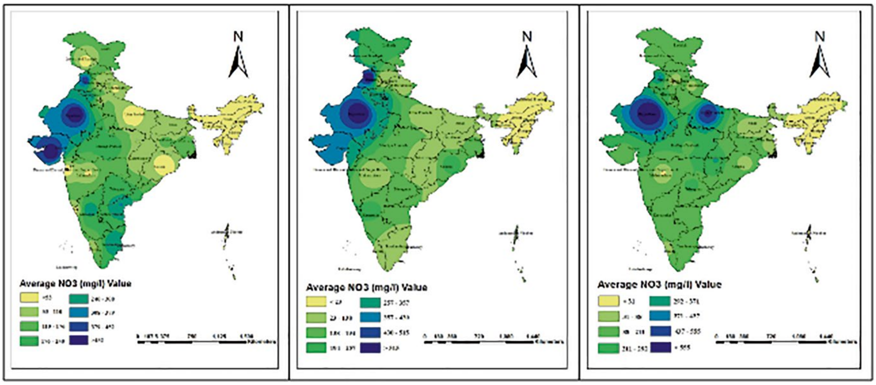
Pradesh, Punjab, and certain parts of Rajasthan exhibited elevated pH levels. However, by 2020, the situation had worsened across India, with many states experiencing elevated pH levels, including Delhi, Haryana, Himachal Pradesh, Jammu and Kashmir, Karnataka, Punjab, Rajasthan, Uttar Pradesh, and Uttarakhand. In 2020, the maximum pH was observed in Madhya Pradesh, while the minimum shifted to Tamil Nadu.

In 2021, Kerala recorded both the maximum and minimum pH levels. Notably, fewer states showed high pH levels in 2021 compared to 2020. However, water bodies in Delhi, Haryana, Himachal Pradesh, and Punjab continued to exhibit elevated pH levels.

3.1.2 Nitrate

Fertilizers and manure, containing nitrates and organic nitrogen compounds, often infiltrate groundwater and find their way into surface water from agricultural fields. Elevated nitrate levels render water unfit for drinking. In rivers, lakes, and marine environments, nitrogen and other nutrients, particularly phosphorus, stimulate algae growth. While algae at moderate levels serve as food for aquatic organisms, including fish, excessive nutrient concentrations lead to overgrowth. This disrupts the natural ecosystem and can deplete water oxygen levels, a phenomenon known as eutrophication, which adversely impacts biodiversity, fisheries, and recreational activities. The maximum contamination limit of nitrate in water is set at 50 mg/L.

Figure 4 depicts the spatiotemporal distribution of nitrate in water resources. Rajasthan exhibited the highest nitrate concentration. In 2019, elevated nitrate levels were observed in Rajasthan, Gujarat, and Punjab. By 2020, nitrate concentration peaked in certain water resources of Rajasthan, Punjab, and Delhi. In 2021, while nitrate levels decreased in Gujarat, they increased in Uttar Pradesh and persisted in Rajasthan.



(a) Year 2019 (b) Year 2020 (c) Year 2021

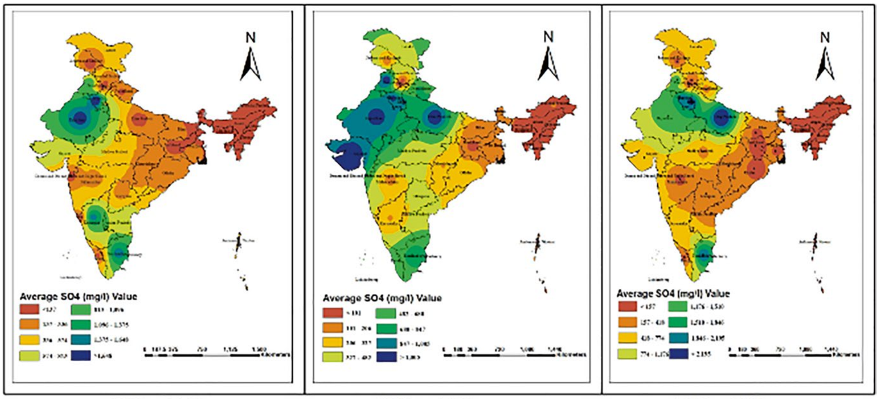
Fig. 4 Spatiotemporal distribution of Nitrate in Indian Water Resources

3.1.3 Sulfate

Sulfates and sulfuric acid play crucial roles in various industries, including fertilizer production, chemical synthesis, dyeing, glassmaking, paper manufacturing, soap production, textile processing, and the formulation of fungicides, insecticides, astringents, and emetics (Butter, 1985). These compounds are also utilized in mining, wood pulp processing, metal production, plating industries, sewage treatment, and leather processing. For instance, alum, or aluminum sulfate, aids in sediment removal during drinking water treatment processes, as demonstrated by McGuire et al. (1984), who found copper sulfate effective in algae control in both treated and untreated water sources.

However, studies have indicated that consuming sulfate in high concentrations can induce a laxative effect. The US Environmental Protection Agency (EPA) (1999) reported that approximately 68% of individuals exposed to water with sulfate levels ranging from 1000 to 1500 mg per liter experienced laxative effects. Even at lower concentrations, such as 750 mg per liter, water consumption led to reports of a laxative effect. Interestingly, water containing 1000 mg of sulfate per liter had differing outcomes, indicating individual variations in tolerance levels. Complaints regarding a noticeable taste arise as sulfate concentrations in water exceed 500 mg per liter.

Figure 5 illustrates the spatiotemporal distribution of sulfate in Indian water resources. In 2019, Haryana and Rajasthan exhibited exceptionally high sulfate concentrations exceeding 3000 mg/L. By 2020, elevated sulfate levels were observed in several Indian states, including Gujarat, Haryana, Punjab, Rajasthan, and Uttar Pradesh, reaching around 2500 mg/L. In 2021, Uttar Pradesh, Tamil Nadu, Delhi, and Haryana experienced very high sulfate concentrations ranging from 4000 to 5600 mg/L.



(a) Year 2019 (b) Year 2020 (c) Year 2021

Fig. 5 Spatiotemporal distribution of Sulfate in Indian Water Resources

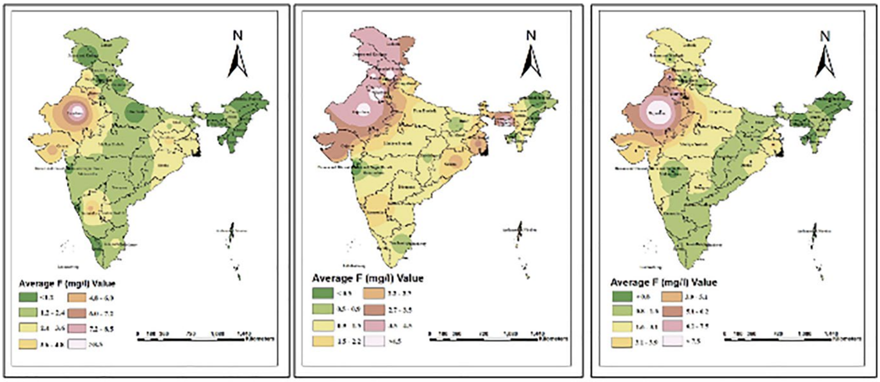
3.1.4 Fluoride

Fluoride contamination in drinking water has become a global concern due to its potential health impacts. While fluoride is essential in small amounts, concentrations exceeding 1.5 mg/L can pose health risks to individuals. Human activities such as the use of fluoride-containing fertilizers, rodenticides, fumigants, herbicides, and insecticides can elevate fluoride levels in water sources. Exceeding recommended fluoride levels can lead to severe health issues for individuals of all ages, including infants, children, and adults.

Figure 6 illustrates the spatiotemporal distribution of fluoride in Indian water resources. In 2019, fluoride concentrations exceeded the maximum contamination level (MCL) in 19 states of India. Rajasthan recorded the highest concentration at 19.5 mg/L, while Jammu and Kashmir reported no detectable fluoride (0 mg/L). By 2020, Haryana recorded the highest concentration at 12.85 mg/L and Nagaland the lowest at 0.31 mg/L. Notably, fluoride concentrations in Jammu and Kashmir increased to 8.58 mg/L, while Rajasthan's levels decreased to 9.65 mg/L. In 2021, twenty states in India reported fluoride concentrations above the MCL. Rajasthan exhibited the highest concentration at 22.30 mg/L, while Arunachal Pradesh recorded the lowest at 0.5 mg/L. Jammu and Kashmir reported a concentration of 2.5 mg/L in 2021.

3.2 Generation of Database

The Water resource assessment database utilized in this study primarily originates from the Central Ground Water Board (CGWB) databases, covering data from 2019 to 2021. In this analysis, Inverse Distance Weighted (IDW) interpolation techniques were employed to map water quality parameters such as pH, sulfate, nitrate, and fluoride across India for the years 2019, 2020, and 2021 (see Figs. 3, 4, 5 and 6).



(a) Year 2019 (b) Year 2020 (c) Year 2021

Fig. 6 Spatiotemporal Distribution of Fluoride in Indian Water Resources

These maps offer a visual representation of water quality variations on a national scale, facilitating the identification of geographical patterns and trends over the specified time period.

3.3 Risk Assessment

ECs present a significant danger to humans, even in small quantities. The detrimental impact of these contaminants extends to both terrestrial and aquatic life forms, including the health of human beings (Gheorghe et al., 2016; Liu et al., 2020; Rout et al., 2021). People are fundamentally uncovered to Endocrine-Disrupting Chemicals through the utilization of polluted nourishment and drinks, which can be defiled by organisms, soil, water, plants, and creatures. This exposure can lead to biomagnification and bioaccumulation, especially in species at the top of the food chain. Numerous studies investigating the long-term effects of EC compounds have demonstrated significant impacts (Fig. 7).

Buzea et al. (2007) highlighted the potential harmful effects of nanoparticles (NPs) on human health, which can be influenced by various factors including pre-existing illnesses, heredity, size, shape, exposure, chemistry, electromagnetic characteristics, and aggregation state of the NPs. Recent studies on epidemics have demonstrated a clear association between high levels of air pollution and increased incidences of heart and lung diseases, as well as respiratory and cardiovascular problems, cancer, and mortality rates. Additionally, certain nanomaterials have been found to generate reactive oxygen species and exhibit cytotoxic effects in laboratory settings. Moreover, they possess the capability to traverse cell membranes and overcome barriers within living organisms such as the blood-brain barrier (Foley et al., 2002; Kim et al., 2006; Shosaku, 2006; Xia et al., 2006).

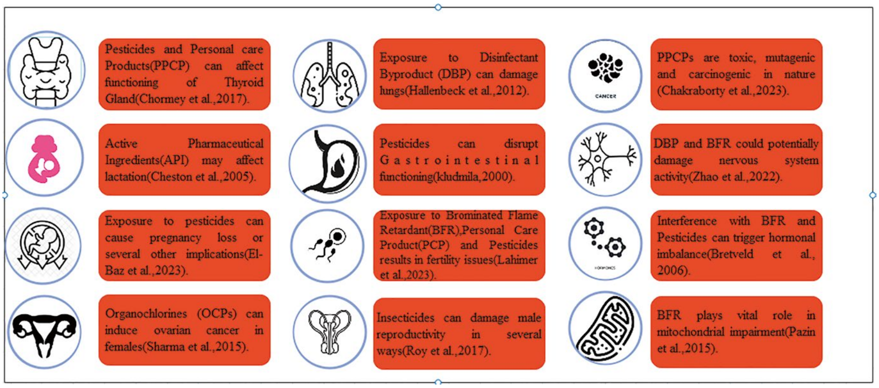


Fig. 7 Health Impact Assessment Impact of Emerging Contaminants

4 Results and Discussion

4.1 Eco-Friendly Remedies

The escalation of living standards, urban expansion, and alterations in agricultural and industrial practices have contributed to the proliferation of emerging contaminants (ECs) in water bodies. Addressing this challenge necessitates the implementation of efficient and cost-effective treatment technologies capable of effectively removing ECs from water sources.

4.2 Green Technology

The concept of green technologies encompasses various environmentally friendly practices and innovations aimed at mitigating the adverse effects of human activities on the environment. The primary goal of green technologies is to foster sustainability and cultivate a cleaner and healthier environment for future generations. To combat ECs, it is feasible to deploy effective and economically viable treatments such as microbial technology, biopreparations, and integrated ecotechnologies.

4.2.1 Microbial-Mediated Technology

Biological remediation involves addressing the presence of non-biodegradable inorganic compounds by either sequestering the harmful compound or converting it into a less harmful form. Microbial-mediated technology for pollution abatement utilizes microorganisms and their byproducts to degrade pollutants, resulting in their complete conversion into water and carbon dioxide for organic pollutants or transformation into less detrimental forms. This technology encompasses various approaches, including bacterial inoculants, microalgal technology, microalgal-bacterial technology, fungal technology, and other innovative methods. Microbial technology offers a cost-effective solution with minimal adverse environmental effects, featuring advantages such as reduced secondary pollution, simplified operation, and resilience, requiring only nominal additional resources. Moreover, it can be conveniently applied on-site, minimizing disruption to the current state. Unlike other methods that merely transfer pollutants from one environmental medium to another, microbial technology enables the complete degradation of targeted pollutants (Gao et al., 2018; Gavrilescu, 2010; Luka et al., 2018; Srivastava et al., 2014; Tekere, 2019).

Swiatczak and Cydzik-Kwiatkowska (2018), Huang et al. (2015), Hashim et al. (2014), Sitarek et al. (2017), Gao et al. (2018), Wang et al. (2010), Monica et al. (2011), and others have applied microbial inoculants containing different bacterial strains for the removal of various contaminants from water sources, including total nitrogen, nitrate nitrogen, total phosphate, turbidity, total suspended solids, total dissolved solids, biological oxygen demand, and chemical oxygen demand. Innovative microalgal approaches employed by Wang et al. (2010), Katam and Bhattacharyya (2018), Li et al. (2020), Posadas et al. (2013), Alcantara et al. (2015), Koreiviene et al. (2014), Boelee et al. (2011), He et al. (2013), Mujtaba and Lee (2017), Zhang et al. (2018), Ahmad et al. (2013), Samori et al. (2013), Sutherland and Ralph (2019), Garcia-Galan et al. (2020), and Matamoros et al. (2016) have successfully eliminated various contaminants from water sources, including caffeine, endocrine-disrupting compounds (EDCs), personal care products (PCPs), insecticides, coliforms, ammonium, total organic carbon, and others. Additionally, a combination of bacterial and microalgal inoculants has been effective in remedying pharmaceutical compounds such as paracetamol, sulfamethoxazole, sulfamethazine, sulfadiazine, ibuprofen, naproxen, salicylic acid, triclosan, propylparaben, microcystin-RR, as well as pollutants like orthophosphate, dissolved organic carbon, and more as reported by Zhang et al. (2013), Wang and Hu (2018), Lopez-Serna et al. (2019), Matamoros et al. (2016), Wu et al. (2010), Ncibi et al. (2017), Choi et al. (2018), and Su et al. (2011) (Table 2).

4.2.2 Bio-Preparations

Bio-preparations refer to substances that are derived from living organisms or their byproducts. A wide range of materials, including chemical substances, energy, and resources obtained from renewable biological sources, are involved in these preparations. Bio-preparations like bio-coagulants and flocculants help particles in water treatment processes clump together and settle down. Various bio-preparations have been investigated for their efficacy in eliminating pollutants from water bodies like.

- Biocoagulants
- Biosorbents

Biological adsorbents are utilized to remove pollutants and contaminants from various environments. Another type of bio-preparation involves the formulation of micro-or macronutrients, which are essential for the growth and development of organisms. Biostimulating agents are also considered bio-preparations, as they enhance the physiological processes of living entities. Lastly, bio-carriers are materials that facilitate the delivery or transportation of bioactive substances. Overall, bio-preparations play a crucial role in harnessing the potential of renewable biological resources for various applications. Bio-preparations are a cost-effective, eco-friendly, and user-friendly technology that promotes energy efficiency. This innovative technology can be derived from readily available natural resources, resulting in reduced production costs (Limin et al., 2010; Singh et al., 2003).

Table 2 List of Microbial Agents and their Efficiency

Target Pollutant	Microbial Agents	Removal Efficiency
Total Nitrogen	Bacterial Inoculant	71–77.8%
	Microalgae	66.67–92.3%
Nitrate Nitrogen (NO_3-N)	Bacterial Inoculant	91%
	Microalgae	75.5%
Ammonium Nitrogen (NH_3)	Bacterial Inoculant	20–94.2%
	Microalgae	95–100%
	Microalgae + Bacterial Inoculant	78%
Total Kjeldahl Nitrogen (NH_3 + NH_4^+)	Microalgae	98.3%
	Microalgae + Bacterial Inoculant	88.3 ± 1.6%
Ammonium (NH_4^+)	Microalgae	82.4–100%
Inorganic Nitrogen	Microalgae	88.6–96.4%
Inorganic Phosphate	Microalgae	88.6–96.4%
Total Phosphate	Bacterial Inoculant	7.8–72.2%
	Microalgae	67.5–100%
Phosphate or Ortho Phosphate (PO_4^{3-})	Microalgae	85.6–100%
	Microalgae + Bacterial Inoculant	64.8–100%
Biological Oxygen Demand	Bacterial Inoculant	85%
	Microalgae	98.7%
Chemical Oxygen Demand	Bacterial Inoculant	38–88.8%
	Microalgae	81.82–98.3%
	Microalgae + Bacterial Inoculant	98.2–96.7%
Total Dissolved Solids	Bacterial Inoculant	91%
	Microalgae	98.2%
Total Suspended Solids	Bacterial Inoculant	55%
Turbidity	Bacterial Inoculant	85.6%
Total Organic Carbon	Microalgae + Bacterial Inoculant	91 ± 3%
	Microalgae	86–90%
Dissolved Organic Carbon	Microalgae + Bacterial Inoculant	26%
Inorganic Carbon	Microalgae	57–98%
Paracetamol	Bacterial Inoculant	87.1–100%
Sulfamethoxazole		98.8%
Sulfamethazine		20.5%
Sulfadiazine		17.5%

(continued)

Table 2 (continued)

Target Pollutant	Microbial Agents	Removal Efficiency
Total Coliform	Microalgae	99%
Fecal Coliform		99%
EDC, PCP		> 70%
Alachlor		100%
Linuron		100%
Cybutryne		100%
Atrazine		100%
Chlorfenvinphos		100%
Fenthion oxon		100%
Malaoxon		100%
Fenthion sulfoxide		100%
Terbuthylazine		100%
Azynphos ethyl		100%
Microcystin-RR	Microalgae + Bacterial Inoculant	64.9–99.7%
Ibuprofen	Microalgae	94–99%
Naproxen		52%
Salicylic acid		98 ± 2%
Triclosan		100%
Propylparaben		100%
Caffeine	Microalgae + Bacterial Inoculant	95%

4.2.3 Integrated Ecotechnologies

Integrated ecotechnologies represent a holistic approach that integrates physico-chemical, biotechnological, and engineering methodologies to effectively degrade specific pollutants. This approach involves utilizing various combinations of components such as bacteria, microalgae, aeration, biological aerated filters (BAF), biological contact oxidation, biofilms, biocatalysts, bio-carriers, natural coagulants, and structural modifications to achieve pollutant removal. A wide range of contaminants can be targeted using these ecotechnologies, including:

- Gravel contact oxidation system.
- Step-feed biological contact oxidation processes (SBCOP)/Inter-recycle contact biological oxidation processes (IBCOP).
- Bamboo biofilm reactor.
- Green Bridge.
- Combined technology (integrating biological, chemical, and engineering processes).
- Enhanced membrane aerated biofilm reactor (MABR).
- Enhanced ecological floating beds.
- Biocoagulation-biofiltration.
- Ecosystem activation system.
- Integrated artificial aeration and biological zeolite system.
- Reclamation pond constructed wetland.

- Hybrid pond constructed wetlands and conventional wastewater treatment plants.
- Integrated cascade biofilm reactor (CSBR) and One-Step biofilm reactor (OSBR).

These ecotechnologies excel in maintaining reliability and longevity in pollutant remediation, requiring less time and physical space. They are also resilient and adaptable to specific technological requirements. Integrating multiple processes offers greater benefits compared to individual treatment methods (Fang et al., 2016; Joshi & Joshi, 2008; Sheng et al., 2012).

5 Conclusion

Numerous research studies have highlighted the presence and distribution of emerging contaminants (ECs) in various water resources, including surface water, groundwater, drinking water, and treated wastewater from Sewage Treatment Plants (STPs) and Common Effluent Treatment Plants (CETPs). These contaminants can adversely affect aquatic and terrestrial wildlife, vegetation, and human communities by disrupting their natural hormonal functions. They have the potential to persist, accumulate in organisms, and induce toxicity. Unfortunately, conventional wastewater treatment plants (WWTPs) are often unable to effectively remove these substances, leading to residual concentrations in surface and groundwater, thereby posing a significant environmental risk (Eggen et al., 2014; LaLone et al., 2017; Escher & Fenner, 2011).

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Techniques of Bioremediation for Polluted Environments: Overview, Benefits, Drawbacks, and Future Prospects

Shazia Akhtar and Suman Naithani

1 Introduction

Due to the escalating global population, human activities are expanding daily, resulting in significant environmental pollution from various sources of hazardous chemicals (Raghunandan et al., 2014 & 2018). Effects of industrialization, such as reduced natural resources, increased carbon emissions, and pollution, adversely affect human health and the environment (Ahuti, 2015). Industrialization influences economic and social development and necessitates technological advancements (Mgbemene et al., 2016). The widespread use of pollutants during the industrial revolution has resulted in severe health issues including skin diseases, nervous system damage, heart failure, and kidney problems. Advanced technology and industrial processes not only have adverse effects but also contaminate the environment. Harmful gases, chemicals, and xenobiotics are unintentionally released into the environment due to industrial activities. Bioremediation, utilizing the inherent biological activity of ecosystems, offers a solution to eliminate or detoxify harmful substances (Siddiquee et al., 2015). Bacteria, fungi, or plants can degrade or detoxify potentially dangerous chemicals for the benefit of human health (Qazilbash, 2004). Bioremediation involves the biological breakdown or transformation of organic or inorganic waste into typically nontoxic chemicals, utilizing low-tech, low-cost techniques that are legally and socially acceptable (Su, 2014).

Microorganisms, obtained from other areas or naturally contaminated zones, can be introduced to polluted sites to facilitate chemical processes through metabolic activity (Siddiquee et al., 2015). Various methods, such as biofilters, bioventing, biosorption, composting, bioaugmentation, bioreactors, land farming, and biostimulation, employ bioremediation principles (Qazilbash, 2004). Khan et al. (2016)

S. Akhtar · S. Naithani (✉)
Department of Environment, Graphic Era (Deemed to be University), Dehradun, India
e-mail: suman_geu_naithani@geu.ac.in

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emphasized the importance of considering factors like soil type, temperature, pH, oxygen availability, nutrients, and microbial populations when managing and enhancing bioremediation operations. The ability of microbial communities to degrade pollutants poses another challenge. Bioremediation offers a unique approach to removing contaminants from various environments, including groundwater, industrial effluents, solids (soils, sediments, and sludge), gases emitted by soil vents, industrial emissions, and raw materials from industrial processes.

2 Sources of Heavy Metals in the Environment

Table 1 presents a compilation of environmental sources of heavy metals, encompassing both natural occurrences and those induced by human activities. Heavy metals can find their way into various environmental compartments such as soil, water, air, and their interfaces, as a result of both natural processes and human interventions.

2.1 Natural and Anthropogenic Sources of Heavy Metal

Various studies have identified sources of heavy metals, encompassing both natural phenomena and human activities. These metals are generated by natural processes and are released into the environment through a variety of mechanisms. Natural sources include volcanic eruptions, sea salt sprays, forest fires, rock weathering, biogenic processes, and wind-blown soil particles. When metals migrate from their original locations to new environmental compartments, natural weathering processes come into play.

Heavy metals exist in different chemical forms such as hydroxides, oxides, sulfides, sulfates, phosphates, silicates, and organic compounds. Common heavy metals include lead (Pb), nickel (Ni), copper (Cu), chromium (Cr), cadmium (Cd),

Table 1 Natural and anthropogenic sources of heavy metal in the environment

Natural source	Anthropogenic source
Erosion and abrasion of rocks	**Industrial emissions** (SO_2), (NO_x), (CO), (PM), (VOCs), and hazardous air pollutants (HAPs)
Forest fires biogenic source	**Transportation** (CO), (NO_x), (PM), (VOCs), (SO_2), and (CO_2)
Particles released by vegetation	**Agricultural activities** (CH_4), (NH_3), (PM), and (NO_x)
Weathering of minerals aerosol formation	**Residential heating and cooking** (CO), (PM), (VOCs), (SO_2), and (NO_x)
Volcanic eruption	**Construction and demolition** (PM), (VOCs), (NO_x), and asbestos
Oceanic and terrestrial volatile organic compounds (VOCs)	**Mining and quarrying** (PM), (SO_2), (NO_x), and heavy metals

arsenic (As), mercury (Hg), selenium (Se), zinc (Zn), and arsenic (As), which can pose risks to both human and animal health (Ali et al., 2021).

Various activities such as runoff, industrial processes, drainage, irrigation, mining, metallurgical processes, and others contribute to the release of pollutants into different components of ecosystems. Industrial areas are often significant sources of naturally released metals into the atmosphere. Heavy metals like lead, arsenic, copper, zinc, nickel, vanadium, mercury, selenium, and tin are emitted into the environment through activities such as car exhaust, smelting, pesticide use, and fossil fuel combustion. Human activities play a significant role in environmental degradation, as the production of goods often caters to the demands of a growing population.

3 Materials and Methods

3.1 Bibliographic Research and Data Collection

The data were gathered from research papers obtained from PubMed, Scopus, Web of Science, Google Scholar, and Environmental Science databases. Keywords used included "bioremediation," "biodegradation," "microbial remediation," "contaminants," "pollutants," and specific contaminants like "oil spill" and "heavy metals." Studies of peer-reviewed articles, on bioremediation of contaminants (heavy metals, organic pollutants, etc.) and studies published in the last 10 years were also considered.

3.2 Bioremediation Treatment Methods

Bioremediation's success hinges on demonstrating sufficient evidence of pollutant degradation. However, a critical challenge lies in determining the level of efficacy and completeness necessary to achieve satisfactory outcomes. Natural attenuation, a remediation method, relies on natural processes to clean up or reduce pollution in soil and groundwater without human intervention (CLU-IN, 2016). It primarily serves as a monitoring tool to ensure that more aggressive cleanup measures are unnecessary. The effectiveness of bioremediation is influenced by both abiotic and biotic factors.

Current monitoring techniques assess the reduction of pollutants and their breakdown products to regulated levels, often employing toxicity testing on individual organisms or species to detect any induced alterations that could lead to residual toxicity (Chauhan & Varma, 2009). However, relying solely on these methods for pollutant assessment may yield unreliable indications of residual toxicity. Examining the response of the entire community, rather than focusing on a single species, may offer a more comprehensive predictor of long-term toxicity. Human intervention may become necessary for a more successful cleansing process once sufficient evidence is provided.

There are two remediation methods: ex situ and in situ. Ex situ remediation involves removing contaminated material from the environment and treating it away from the source, while in situ remediation involves treating the contaminated area directly.

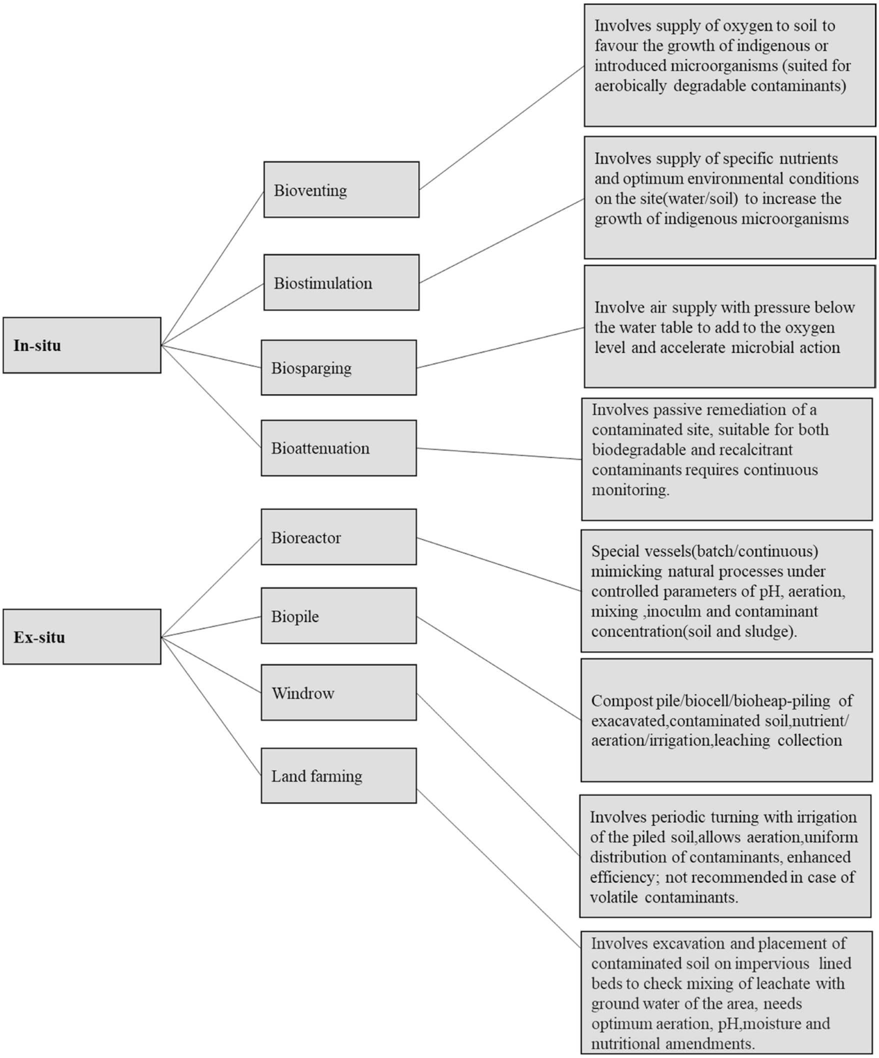

Fig. 1 Approaches to bioremediation for environmental cleanup

Some treatment techniques can be applied both ex situ and in situ, and solutions may involve either mobilizing pollutants to remove them from a specific location or immobilizing pollutants to prevent them from entering certain areas such as water tables.

Ex situ methods are applied to excavated or pumped soil and groundwater. Techniques such as composting, biofilters, and biopiling are commonly used. Ex situ remediation is preferred for smaller projects where extensive soil excavation is undesirable, although soil movement may disrupt preexisting soil horizons to a greater extent. The ultimate goal in bioventing is to achieve microbial transformation (Fig. 1) of pollutants to a harmless state **by** addition of nutrients and moisture to enhance bioremediation (Philp & Atlas, 2005). The two basic criteria for **successful** bioventing are to maintain aerobic conditions and to obtain reasonable biodegradation rates, natural **hydrocarbon**-degrading microorganisms must be presented in enough concentrations and hence air injection rate is one of the main parameters for pollutant dispersal. "In **situ**" treatment of heavy metals generally involves pumping oxygen/nutrients (bioventing/biostimulation) into the **soil** (Kapahi & Sachdeva, 2019).

3.2.1 Bioventing

Bioventing aims to promote bioremediation by facilitating microbial transformation of contaminants into harmless substances through the addition of nutrients and moisture (Philp & Atlas, 2005). It relies on the presence of natural hydrocarbon-degrading microorganisms in sufficient quantities to sustain aerobic conditions and achieve optimal biodegradation rates, highlighting the importance of air input rate in pollution remediation. "In situ" treatment of heavy metals often involves oxygen and nutrient injection into the soil through processes such as bioventing (Kapahi & Sachdeva, 2019).

3.2.2 Biostimulation

Microbial turnover of chemical pollutants is influenced by various factors including the type of organic pollutant, temperature, oxygen levels, pH, redox potential, and nutrient content (carbon, nitrogen, and phosphorus) (Bundy et al., 2002). Another biostimulation strategy involves using biodegradable substances as primary substrates and the pollutant as a secondary substrate, regulated at controlled rates. Temperature plays a crucial role in boosting biomass activity, thereby promoting biostimulation; however, temperature control is feasible only in well-designed systems such as slurry bioreactors and enclosed vessel composting (Fulekar et al., 2012). For instance, Fulekar et al. (2012) employed aerobic bacteria isolated from heavy metal-contaminated sites to remove Fe, Cu, and Cd in a biostimulation study, utilizing various bacterial species collected from polluted environments.

Biostimulation for heavy metals depends on the supply of nutrients (carbon, nitrogen, phosphorus), temperature, oxygen, pH, redox potential, and concentration and type of organic pollutant for accelerating the microbial turnover of chemical pollutants (Carberry & Wik, 2001; Bundy et al., 2002; Al-Sulaimani et al., 2010). Addition of biodegradable compounds which act as primary substrates is another strategy of biostimulation where the pollutant is degraded as a secondary substrate but at acceptable rates.

3.2.3 Biosparging

This method involves injecting air into the subsurface soil to enhance the biological degradation of pollutants by naturally occurring microorganisms. The efficiency of biosparging is influenced by two main factors: the biodegradability of pollutants and the permeability of the soil (Philp & Atlas, 2005). When bacteria are under stress, they produce metal-adsorbing compounds that chemically react with contaminants, leading to their precipitation. Biosparging creates an aerobic environment through the addition of oxygen, facilitating the degradative activity of indigenous bacteria and ultimately leading to pollutant destruction (Adams & Reddy, 2003).

3.2.4 Bioattenuation

The process involves either immobilizing or transforming pollutants into less hazardous forms (Smets & Pritchard, 2003). Compared to cleanup systems based solely on physical and chemical methods, the costs of this approach are significantly lower, typically by 80 to 90% (Davis et al., 1994; Mulligan & Yong, 2004). Acinetobacteria have been observed to participate in the bioattenuation process, naturally removing metals like U, Al, Cd, Co, Cu, Mn, and Ni (Fauziah et al., 2017). Conversely, proteobacteria-mediated bioattenuation has proven effective in removing metals such as As, Ni, and Al (Schmidt et al., 2005).

3.2.5 Bioreactor

A bioreactor, as its name suggests, utilizes microorganisms to remove toxins from pumped groundwater or wastewater. It serves as a biological processing device used both "in situ" during the liquid (slurry) and solid (solid) phases of soil decontamination. Bioreactors can operate in batch, fed-batch, sequencing batch, multistage, and continuous modes, with their performance influenced by overall economics and capital investment. By optimizing environmental conditions to promote microbial growth, bioreactors enhance the activity of naturally occurring cells. Key parameters for bioreactors include temperature, pH, moisture, inoculum concentration, aeration rate, agitation rate, and substrate concentration. The biological activity within a bioreactor can be manipulated to expedite bioremediation by adjusting these parameters. Factors such as food intake regulation, controlled bioaugmentation, enhanced bioavailability of contaminants, and mass transfer constraints affect the bioremediation process within a bioreactor.

Anaerobic upflow (ANFLOW) bioreactors operate by initiating the process from the bottom of the column and progressing upwards, akin to an ion exchange process, to remove heavy metals (Rivera, 1983). Membrane bioreactor (MBR) systems have demonstrated high bioremediation rates for various metals, such as Cu(II), Pb(II), Ni(II), and Zn(II). Fixed bed bioreactors have been shown to enhance metal removal efficiency, particularly for Cu2+, Pb2+, Cd2+, Co2+, Ni2+, Zn2+, Mn2+, and Fe3+, by strains of Pseudomonas aeruginosa, mitigating numerous health hazard chemicals (Ibrahim et al., 2019).

Additionally, membrane bioreactors have been effective in removing lead, nickel, arsenic, cadmium, and antimony (Komesli, 2014). Aftab et al. (2017) demonstrated successful recovery of lead (Pb) and chromium (Cr) metals from wastewater using an osmotic membrane bioreactor (OMBR). Furthermore, Barros et al. (2006) reported the elimination of 90% of heavy metals (nickel and chromium) in an alkaline pH fixed packed bed bioreactor through biosorption within 20 days.

3.2.6 Biopiling

Before being deposited in a treatment area, excavated soil is blended with soil additives. Aerated biopiles utilize perforated pipes and blowers to regulate biodegradation by controlling the flow of oxygen, which can impact other factors such as pH

(Ding et al., 2017). To prevent further contamination, the remediated soil is placed in a liner, and it may also be covered with plastic to minimize runoff, evaporation, and volatilization.

3.2.7 Composting

Nutrients are introduced into the soil to enhance aeration and activate indigenous microorganisms. Composting is conducted in a separate container before being applied to the soil. Microorganisms' organic matter adsorption capabilities are utilized in compost bioremediation (Chen et al., 2020). Composting stands out as one of the most cost-effective methods for soil bioremediation and can be employed on both large and small scales. It is particularly effective for less complex pollutant remediation, offering versatility for soils affected by various organic pollutants and heavy metals. Utilizing organic waste for soil restoration reduces the need for storage and treatment. Moreover, organic matter from composting enriches soil structure and quality. As nutrients for bacteria are gradually supplied through composting, it is often employed for long-term remediation rather than immediate treatments like biostimulation.

3.2.8 Windrow

Windrows are engineered to regularly redistribute piled contaminated soil to hasten the degradation process by indigenous or transient hydrocarbonoclastic bacteria present within the polluted soil. The frequent turning of contaminated soil enhances the bioremediation rate. Anaerobic zones formed within polluted soil during windrow formation promote the emission of the greenhouse gas methane (CH4) (Hobson et al., 2005).

However, because windrow treatment requires periodic turning, it may not be suitable for remediating soils contaminated with toxic volatile compounds. Humic compounds have demonstrated effectiveness in removing heavy metals such as Cd and Ni (Zhang et al., 2016). This method is utilized to separate metals such as Cu, Zn, Fe, Mn, and Cd (Achiba et al., 2009).

3.2.9 Land Farming

To facilitate waste aeration, contaminated soil is either mixed with fertilizers and tilled into the ground or placed in lined beds and regularly turned over or tilled. However, this method primarily targets the top layer and may not be optimal for deeper remediation. Land farming differs from composting in that it integrates contaminated soil into uncontaminated soil. Lighter hydrocarbons, which are easily volatilized, are typically found in the upper cleaning zone (Silva-Castro et al., 2012). Regular tilling of the material promotes aeration, increases oxygen availability as electron acceptors, and enhances volatilization. Microbiological and oxidative mechanisms decompose, transform, and immobilize contaminants. Adjusting the moisture content, aeration frequency, and soil pH can expedite pollutant breakdown (Maila & Colete, 2004).

4 Mechanisms of Bioremediation

Microorganisms are ubiquitous in heavy metal-contaminated soil and possess the ability to swiftly convert heavy metals into nontoxic forms. In bioremediation techniques, microorganisms transform organic contaminants into final byproducts, such as less hazardous compounds, carbon dioxide, and water, or metabolic intermediates that serve as essential building blocks for cellular growth. Microorganisms defend themselves in two ways: by producing enzymes that break down the contaminants of interest and by developing resistance to heavy metals in soil and water. Various bioremediation strategies leverage microbial processes, including bioleaching, bioaccumulation, biomineralization, metal-microbe interactions, and biosorption. Microorganisms utilize chemicals for growth and development, thereby removing heavy metals from the environment.

4.1 Biosorption

The process of removing heavy metals or other contaminants from fluids using living or dead biomass is termed biosorption (Kisielowska et al., 2010a, b). Surface adsorption is employed to facilitate the biosorption process, which necessitates the presence of bacteria. The outer cell membrane governs bacterial sorption characteristics, with chemically active groups binding metals onto cell surfaces. This interaction is often driven by ion transfer interactions between active groups capable of interacting with the negative potential of various cell structures and microorganisms, as well as metal cations (Kręgiel et al., 2008).

4.2 Bioaccumulation

When a pollutant accumulates more rapidly than it is eliminated, it is termed bioaccumulation. As a result, the contaminant remains within the organism, gradually building up in concentration (Chojnacka, 2010). The toxicokinetic process of bioaccumulation alters the vulnerability of organisms to toxins. Typically, organisms can tolerate a certain concentration of chemicals before they become harmful and pose a threat to the organism's health. However, the sensitivity of organisms to chemicals varies greatly depending on the species and the specific chemicals involved (Mishra & Malik, 2013).

4.3 Biotransformation

In microorganisms, heavy metals undergo cycles of oxidation, reduction, methylation, and demethylation, facilitated by the enzymatic systems of microorganisms. Gram-positive bacteria present in tannery waste have been observed to convert hazardous chromium (VI) into less toxic chromium (III), potentially aiding in the removal of the metal from the environment. These metal reduction methods, although high-risk/high-reward, have practical applications (Kisielowska et al., 2010a, b).

Moreover, precious metal ions can be converted into metallic forms, such as gold or silver, by various microbes or microscopic fungi. This process is crucial for metal recovery as it can occur within vacuoles, on cell surfaces, and in the extracellular environment (Kisielowska et al., 2010a, b; Sklodowska, 2000).

4.4 Biocrystallization and Bioprecipitation

Microbial activity can induce heavy metal complexes to precipitate or crystallize, converting the metal into a less soluble form, thereby reducing its toxicity. Various precipitation and biocrystallization processes, including the formation of microfossils, iron and manganese deposition, and silver and manganese mineralization, are influenced by biogeochemical cycles. Apart from enzymatic action, the galactosides of secondary metabolites can also precipitate metals on the cell's surface or within the cell.

4.5 Bleaching of Heavy Metals

Utilizing bacteria, fungi, and microorganisms in conjunction with their metabolic byproducts, the well-established commercial process known as "bioleaching" is employed to extract metals from minerals and sulfide materials. The fundamental principle behind this technique is to convert sparingly soluble ambient metal compounds, often sulfides, into highly soluble forms, thereby facilitating the easy removal of the metal (Kisielowska et al., 2010a, b). Fungi play a crucial role in managing waste products, extracting metals from low-grade ores, and bioleaching, primarily through two processes: the production of various organic acids such as gluconic, citric, and oxalic acids, and the secretion of chelators. Fungi such as Aspergillus, Penicillium, Rhizopus, Mucor, Alternaria, and Cladosporium are significant contributors to metal leaching due to their biochemical capabilities and their resilience to harsh environmental conditions such as pH and temperature. Bioleaching is particularly useful in situations where conventional chemical or bacterial leaching processes involving organisms like A. ferrooxidans and A. thiooxidans are not viable options (Blaszczyk, 2007).

5 The Potential of Microorganisms to Bioremediate Heavy Metals

Microorganisms can uptake heavy metals through two mechanisms: passive adsorption or active bioaccumulation. Metal-resistant strains have proven effective for heavy metal remediation in individual, consortia, and immobilized forms.

Immobilized microorganisms may offer additional chemisorption sites for heavy metal adsorption. Various microorganisms, including bacteria, fungi, and algae, have been utilized to remediate heavy metal contamination and detoxify polluted environments (Kim et al., 2015).

5.1 Heavy Metal Remediation Capacity of Bacteria

Microbial biomass exhibits a broad spectrum of biosorptive capabilities, and the capacity of individual microbial cells to absorb and degrade heavy metals is influenced by pretreatment methods and experimental conditions. In order to enhance biosorption, microbial cells must adapt to alterations in chemical, physical, and bioreactor parameters (Ayangbenro & Babalola, 2017). Bacteria are significant biosorbents due to their diversity, small size, ability to thrive in controlled environments, and resistance to environmental fluctuations (Srivastava et al., 2015).

5.2 Heavy Metal Remediation Capacity of Fungi and Algae

Algae and fungi play crucial roles in restoring ecosystems to precontaminant levels (Tables 2 and 3). The process of utilizing algae or other plants to extract toxins from the environment or convert them into less harmful forms is known as phytoremediation. Phytoremediation encompasses the removal or biotransformation of contaminants, such as heavy metals and xenobiotics, from wastewater, soil, and air, through the utilization of microfungi or macroalgae. Fungi and algae are highly adaptable organisms capable of thriving in various environments, including autotrophic, heterotrophic, or mixotrophic conditions. Algae play a vital role in natural ecosystems, regulating metal levels in lakes and oceans by breaking down or absorbing hazardous heavy metals and organic pollutants from the air, such as hydrocarbons, pesticides, biphenyls, and phenolics, accumulating them within their structures (Shamsuddoha et al., 2006).

Global efforts to remediate oil spills have successfully utilized water-forming algae, including Aphanocapsa sp., Oscillatoria salina, Plectonema terebrans, and Synechococcus sp. (Brahmbhatt et al., 2012). Algae capable of removing heavy metals include Anabaena inaequalis, Chlorella sp., Stigeoclonium tenue, Synechococcus sp., and Westiellopsis prolifica.

Mycoremediation, a distinct form of bioremediation, employs the mycelium of fungi to remove or filter harmful substances from contaminated areas. Fungal mycelia produce extracellular enzymes and acids that break down cellulose and lignin. Selecting the appropriate fungal species is crucial for targeting specific contaminants in mycoremediation. Fungi, such as Phanaerochaete chrysosporium and Polyporus sp., possess the ability to degrade various hazardous environmental pollutants, including explosives, polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons, and polychlorinated biphenyls (Ayu et al., 2011; Wu & Yu, 2007). Additionally, white-rot fungi have demonstrated potential as oxidizing agents for

Table 2 Metal uptake capacity of different fungal species in heavy metals removal

Fungal strains	Type of metal	Removal technique	Removal capacity or (removal efficiency %)	References
Aspergillus niger	Cr	Biosorption	100.3 mg L^{-1}	Priyadarshini et al. (2021)
Aspergillus fumigates	Pb	Biosorption	85.65 mg L^{-1}	Priyadarshini et al. (2021)
Aspergillus niger	Cu	Biosorption	0.020–0.093 mg kg^{-1}	Mukherjee et al. (2013)
Penicillium chrysogenumXJ-1	Cd	Biosorption	100.41 mg L^{1}	Priyadarshini et al. (2021)
Coprinus comatus	Hg	Biosorption	0.78–6.7 mg kg^{-1}	Falandysz (2016)
Trichoderma brevicompactum QYCD-6	Cr	Bioaccumulation	15,840 mg kg^{-1}	Zhang et al. (2020)
Trichoderma brevicompactum QYCD-6	Pb	Bioaccumulation	13,400 mg kg^{-1}	Bano et al. (2018)
Trichoderma brevicompactum QYCD-6	Cu	Bioaccumulation	35,060 mg kg^{-1}	Zhang et al. (2020)
Trichoderma brevicompactum QYCD-6	Cd	Bioaccumulation	38,410 mg kg^{-1}	Zhang et al. (2020)
Sterigmatomyces halophilus	Zn	Biosorption	(90%)	Bano et al. (2018)
Sterigmatomyces halophilus	Pb	Biosorption	(57%)	Bano et al. (2018)
Acremonium persicinum	Cu	Biosorption	50–100 mg kg^{-1}	Mohammadian et al. (2017)
Aspergillus flavus	Cu	Bioaccumulation	93,650 mg kg^{-1}	Kanamarlapudi et al. (2018)
Saccharomyces cerevisiae	Cr	Bioaccumulation	34,500 mg kg^{-1}	Kanamarlapudi et al. (2018)
Penicillium simplicissimum	Cu	Biosorption	200–250 mg kg^{-1}	Mohammadian et al. (2017)
Penicillium sp.	Co	Biosorption	(77.5%)	González et al. (2019)
Paecilomyces sp.	Co	Biosorption	(93%)	González et al. (2019)
Aspergilus niger	Co	Biosorption	(70%)	González et al. (2019)

breaking down organopollutants due to their lignin-degrading enzymes (Garg et al., 2008).

Fungi are widely utilized as biosorbents for the removal of hazardous metals due to their exceptional metal absorption and recovery capacities in Table 2 (Fu et al.,

Table 3 Efficiency of different algal strains in the removal of heavy metals

S.No.	Microalgal strain	Heavy metal	Mechanism	Time (min)	Removal efficiency or (capacity)	References
1.	*Maugeotia genuflexa*	As	Biosorption	60	96%	Leong and Chang (2020)
2.	*Ulothrix cylindricum*	As	Biosorption	60	98%	Leong and Chang (2020)
3.	*Chlorella vulgaris*	As	Biosorption	180	32.4%	Saavedra et al. (2018)
4.	*Immobilized chlorella* sp.	Cd	Biosorption	–	92.5%	Shen et al. (2018)
5.	*Chlorella vulgaris*	Cr(VI)	Biosorption	600	56%	Leong and Chang (2020)
6.	*Scenedesmus quadricauda*	Cr(VI)	Biosorption	240	100%	Daneshvar et al. (2019)
7.	*Scenedesmus quadricauda*	Cr(III)	Biosorption	120	98.3%	Khoubestani et al. (2015)
8.	*Phormidium* sp.	Pb	Biosorption	40	92.2%	Das et al. (2016)
9.	*Chlorella* sp.	Pb	Biosorption	180	78%	Molazadeh et al. (2015)
10.	*Chaetoceros* sp.	Pb	Biosorption	180	60%	Molazadeh et al. (2015)
11.	*Spirogyra* sp.	Hg	Biosorption	30	76%	Solisio et al. (2019)
12.	*Chlorella vulgaris*	Hg	Biosorption	120	72.9%	Leong and Chang (2020)
13.	*Chlorella sorokiniana*	Cd	Bioaccumulation	4320	65% (11.232 g kg^{-1})	León-Vaz et al. (2021)
14	*Chlorella sorokiniana*	Cu	Bioaccumulation	4320	2.2 g kg^{-1}	León-Vaz et al. (2021)
15	*Chlorella sorokiniana*	As (V)	Bioaccumulation	4320	0.145 g kg^{-1}	León-Vaz et al. (2021)
16	*Chlorella kessleri*	Pb	Biosorption	120	97.1%	Sultana et al. (2020)
17	*Arthrospira maxima*	Fe	Biosorption	20,160	97.9%	Blanco-Vieites et al. (2022)
18	*Chlamydomonas reinhardtii*	Cd	Biosorption	360	90.2%	Pina-Olavide et al. (2020)
19	*Aphanothess* sp.	Pb	Biosorption	30	99.9%	Keryanti and Mulyono (2021)
20	*Neochloris oleoabundans*	Pb	Biosorption	5	93%	Gu et al. (2021)
21	*Scenedesmus obtusus XJ-15*	Hg	Biosorption	180	(95,010 mg kg^{-1})	Huang et al. (2019)
22	*Pleurococcus* sp.	Hg	Biosorption	28,800	86%	Vela-Garcia et al. (2019)

2012). Research indicates that both living and dead fungal cells regulate the adhesion of inorganic materials (Tiwari et al., 2013). Moreover, Srivastava & Thakur (2006) investigated the ability of Aspergillus sp. to extract chromium from tannery effluent, demonstrating that a bioreactor system removed 85% of chromium compared to 65% removal by tannery effluent alone, likely due to the presence of organic contaminants inhibiting organism growth. Lakkireddy and Kües (2017) demonstrated that Coprinopsis atramentaria successfully bioaccumulated Pb2+ at 800 mg/L and Cd2+ at 1 mg/L, making it an effective heavy metal ion accumulator for mycoremediation. Additionally, dead fungal biomass from Aspergillus niger, Rhizopus oryzae, Saccharomyces cerevisiae, and Penicillium chrysogenum has been reported to reduce lethal Cr (VI) to less dangerous Cr (III) (Park et al., 2005). Furthermore, Candida sphaerica has been found to produce biosurfactants with high removal efficiencies for Fe, Zn, and Pb (Luna et al., 2016).

Lentinus edodes mushrooms have been demonstrated to remove up to 60% of pentachlorophenol from soil (Fragoeiro, 2005). Additionally, Penicillium steckii was isolated from soil samples exposed to the pesticide Simazine.

Algae, being autotrophic, produce more biomass and have lower nutritional requirements compared to other microbial biosorbents. Their high-sorption capacity makes them effective in removing heavy metals (Abbas & Ali, 2014). Algae biomass is utilized for adsorption or cell integration in the bioremediation of heavy metal-contaminated wastewater, a process known as phycoremediation (Chabukdhara et al., 2017). The surface of algae contains various chemical compounds that function as metal-binding sites, including carboxyl, phosphate, hydroxyl, and amide (Abbas & Ali, 2014).

Municipal wastewater treatment using microalgae has been extensively researched (Oswald, 1988). Various microalgae species, particularly those rich in nutrients like carbon, nitrogen, and phosphorus, are effective at removing nutrients from wastewater, especially nitrogen and phosphorus. However, the effectiveness of different genera and points of wastewater treatment plants in treating wastewater with microalgae varies (Renuka et al., 2015).

While bacteria are commonly used to degrade hydrocarbons in oil-contaminated areas, some crude oil compounds are difficult to break down. Enzymes produced by microalgae can break down hazardous organic substances, converting petroleum hydrocarbons into less toxic compounds (Yuste et al., 2000).

Kang et al. (2016) investigated the collaboration of bacterial combinations to accelerate the bioremediation of contaminated soil with a mixture of Pb, Cd, and Cu. They found that bacterial combinations outperformed single culture techniques in terms of growth rates, urease activity, and heavy metal resistance. Synergistic effects were observed in the cleaning of multiple heavy metals, with the Pb remediation rate reaching 98.3%, the Cd remediation rate at 85.4%, and the Cu remediation rate at 5.6% after 48 hours. The bacterial combinations exhibited greater effectiveness and resistance to heavy metals compared to single-strain cultures.

6 Conclusion

The initial step toward effective bioremediation is site characterization, which aids in determining the most suitable bioremediation strategy (ex situ or in situ). Ex situ bioremediation processes may incur higher costs due to additional expenses associated with excavation and transportation. However, they can be employed to treat a wide range of contaminants in a controlled environment. Conversely, the installation costs of on-site equipment for in situ bioremediation, along with challenges in adequately monitoring and controlling the subsurface of a contaminated site, may limit the effectiveness of many processes. Therefore, it is apparent that the cost of remediation is not the sole determining factor in selecting the bioremediation approach for each contaminated site. Geological factors such as soil type, depth and type of pollutants, site proximity to human habitation, and performance characteristics of each bioremediation technology must be considered to successfully remediate contaminated sites.

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Himalayan Chir Pine Biomass as an Adsorbent for the Removal of Industrial Dye

Anjas Asrani, Brijesh Prasad, and Rekha Goswami

1 Introduction

Life is indeed a precious and interconnected element with the natural environment, but it faces significant challenges in the northern Himalayan region, particularly due to forest fires. Fallen dry pine leaves, which are around 39% of the total litter (Kurz et al., 2000), often act as kindling for these destructive blazes. The consequences are far reaching, with forest fires causing extensive pollution that impairs air quality and putting the health of both humans and wildlife at risk. In order to reduce the risk of forest fires, we must remove fallen dry leaves from the ground, as they are vulnerable to fires and serve as fuel for forest fires; however, it is also not safe to collect and store these leaves, as 60–80% of fall occurs during the months of July, August, and September (Kurz et al., 2000), which are the hottest months of the year and can further increase the risk of forest fires, as they can catch fires easily.

Pine trees are mostly found in North America, Europe, Asia, and certain parts of Africa. Pine trees are beneficial to both people and the environment. Pine trees help purify air, control soil erosion, provide habitat for various animals, and contribute to biodiversity. Pine trees are also used for landscaping because of their attractive appearance. Pine trees are also used in construction, furniture, and paper production. The resin produced by pine trees is used to make adhesives, varnish, and certain perfumes. The nut of the pine tree is consumed by animals and humans for its nutritional value. The oil extracted from pine is often used in aromatherapy. Although pine trees are evergreen, they shed their needles every year, which

A. Asrani · B. Prasad (✉)
Department of Mechanical Engineering, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India
e-mail: Prasadbrijesh10@geu.ac.in

R. Goswami (✉)
Department of Environment, Graphic Era Hill University, Dehradun, Uttarakhand, India

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increases the risk of forest fires, as dry leaves catch fire easily, and the leaves that have fallen to the ground help the fire spread easily. To prevent forest fire, the leaves must be picked from the ground.

Water is essential for life, and it plays a crucial role in various aspects of daily living, such as for drinking, washing, and cooking. Unfortunately, water bodies are affected by many pollutants such as heavy metals, pesticides, and plastics, which makes water unsafe for consumption. One of the major pollutants that is often released by the textile, paper, and leather industries is dye water. A total of 7 × 10^5 tons of commercial dyes are produced annually, with approximately 10,000 different types (Iqbal & Ashiq, 2007). This amount of dye water could be the cause of water scarcity, as it is not advisable to use for human consumption. To make water clean and safe for consumption, pollutants such as toxins, inorganic compounds, or microbes must first be removed from it. Many filtration methods such as reverse osmosis, UV light filtration, ion exchange, ultrafiltration, ozone, solar distillation (Negi et al., 2021), and many other techniques are used but are not suitable for removing dye color from water. Although screen filtration, chemical precipitation, and electrocoagulation are some techniques that can remove dye color from water, these techniques are very costly (Negi et al., 2023), and some involve using chemicals to clean water, which can damage nature in the long term. To overcome this problem, activated carbon can be a great alternative.

Activated carbon is a highly porous material that is commonly used for the adsorption of organic matter, dyes, heavy metals, and pharmaceuticals from contaminated water (Tonucci et al., 2015). It can be produced by physical activation or chemical activation. In the physical activation process, the precursor material is heated in the presence of an activation agent or in an inert atmosphere, whereas in chemical activation, the chemical activation agent is added before heating. Both processes result in the creation of a porous structure with a large number of micro- and mesopores, which results in a high surface area for adsorption. In previous studies, activated carbon was made from pistachio shells, coconut shells, coal, cotton stalks, rice bran, rice husks, coffee husks, apple pods, cola nutshells, and coal (Ajmal et al., 2003; Bagreev et al., 2004; Bakti & Gareso, 2018; Bello et al., 2021; Dolas et al., 2011; Gong et al., 2009; Ndi Nsami & Ketcha Mbadcam, 2013; Oliveira et al., 2009; Özdemir et al., 2011; Suzuki et al., 2007; Tonucci et al., 2015). If we make activated carbon from pine leaves, we will be able to solve the problem of dye water pollution and forest fires. This will also help reduce the cost of activated carbon, as the raw material is free.

In this study, we introduce a method for preparing activated carbon from waste pine needles through a physical activation process conducted in an inert atmosphere. The objective is to produce chemical-free carbon, ensuring minimal environmental impact. To validate the efficacy of the activated carbon derived from pine needles, we assessed its ability to adsorb dye in wastewater. The wastewater, sourced from the textile industry, served as a real-world test, while artificial wastewater solutions at varying concentrations were also employed for a comprehensive performance evaluation.

Additionally, scanning electron microscopy (SEM) was used to scrutinize the surface structure of the activated carbon, providing visual insights. X-ray diffraction (XRD) was employed to obtain information about the material's structure, while energy dispersive X-ray analysis (EDAX) was conducted to ascertain its elemental composition. Furthermore, the Brunauer-Emmett-Teller (BET) method was applied to quantify the specific surface area of the activated carbon.

2 Materials and Methods

To fabricate the sample of pine-based activated carbon, the pine needles were collected from Nahan, Himachal Pradesh. Initially, the precursor material was thoroughly checked for any other foreign material, including weeds, stones, or any other plant leaves. Then, the precursor material was cleaned with distilled water until all the dirt was removed. The leaves were subsequently soaked in distilled water for 24 h. Following these, the leaves were again thoroughly cleansed with distilled water and carbonized in a muffled furnace at $620°C$, and after 30 min, the leaves were slowly allowed to cool. Then, the carbonized activated carbon was removed from the muffled furnace. The carbonized leaves were then converted into powder with the help of an electric mixer grinder and sieved below 150 microns for further testing.

The wastewater solution was collected from Sara Textiles Village Bhatian, New Bhartgarh Road, Nalagarh, Himachal Pradesh 174,101. The solution was described as a dye solution of crystal violet, which was used to dye the cloth, and the leftover dye water was collected and used to test the adsorption ability of the activated carbon.

It was observed that 0.5 g of pine-based activated carbon was able to adsorb all the dye from 50 ml of wastewater solution within 60 minutes of contact. Furthermore, the smell that was observed from the stock solution was also suppressed after the dye was adsorbed from it, proving the ability of the pine-based activated carbon to remove odor.

Furthermore, to calculate the adsorption isotherms and adsorption kinetics, an artificial wastewater solution was also made. A stock solution of crystal violet dye was prepared at a concentration of 500 ppm(500 mg/l) by dissolving 0.5000 g of crystal violet in a 1 L volumetric flask. The solution was thoroughly mixed with the help of a magnet stirrer to obtain homogeneity. Solutions of various concentrations were made from the same solution diluted with distilled water.

3 Characterization

3.1 Adsorption Study

3.1.1 Dye Removal Rate

A batch adsorption study of crystal violet was performed, and factors such as contact time and initial concentration were examined. The adsorption capacity of the carbon was determined with the help of the formula

$$Qe = \frac{(Co - Ce)V}{W}$$

$$Qt = \frac{(Co - Ce)V}{W}$$

where Qe represents the equilibrium dye concentration of the adsorbent (mg/g), Qt represents the quantity adsorbed at any time t, Co and Ce represent the initial and final concentrations, respectively, of crystal violet in mg/L, V is the volume of solutions in L, and W is the weight of activated carbon in g.

3.1.2 Dye Removal Percentage

The percentage of the carbon was determined using the formula

$$\%rem = \frac{(Co - Ce)}{Co} \times 100$$

3.2 Adsorption Isotherm and Kinetics

3.2.1 Adsorption Isotherm

The adsorption isotherm serves as a crucial tool for elucidating the adsorption and binding potential, along with the surface characteristics of the adsorbent (Goswami et al., 2022). It plays a pivotal role in establishing the equilibrium relationship between the adsorbate and adsorbent under constant temperature and pressure conditions. In this study, our focus revolves around three prominent isotherms, Freundlich, Langmuir, and Temkin, to assess the behavior of the adsorbent during the adsorption process.

The Langmuir isotherm, a foundational model, is employed to characterize the adsorption of molecules onto a solid surface, especially in the context of gases or solutes adhering to a solid substrate. This model explains the development of a single layer of adsorbate on the outer surface of the adsorbent. Once this monolayer is formed, further adsorption comes to a halt. The Langmuir model is generally plotted between $\frac{1}{Ce}$ on the X-axis and $\frac{1}{Qe}$ on the Y-axis.

The Langmuir isotherm equation is given by

$$\frac{Ce}{Qe} = \frac{Ce}{Qm} + \frac{1}{KLQm}$$

$$RL = \frac{1}{1 + KL.Co}$$

where Qm denotes the maximum adsorption capacity (mg/g) and KL is the Langmuir constant.

The Freundlich isotherm, a mathematical model, is employed to explain the adsorption of molecules onto the surface of either a solid or a liquid. Widely utilized for characterizing adsorption on heterogeneous surfaces, this model offers insights into the adsorption characteristics.

When using the Freundlich model, the typical plot involves Log Ce on the X-axis and Log Qe on the Y-axis, providing a convenient representation for analysis.

The Freundlich isotherm equation is given by

$$\log Qe + \left(\frac{1}{n}\right) LogCe$$

where *n* is the empirical parameter for the adsorption intensity and where Kf is the Freundlich constant.

The Temkin isotherm provides a mathematical model for the relationship between the adsorbate's concentration in the liquid phase and the adsorbate's adsorption onto the solid surface at equilibrium. The Temkin isotherm equation is given by

$$Qe = \beta lnAt + \beta lnCe$$

$$\beta = \frac{RT}{b}$$

where At stands for the equilibrium binding constant (L/mg) corresponding to the maximum binding energy, b is Temkin isotherm constant, β is linked to the heat of sorption. R denotes the gas constant (8.314 J/mol K), and T represents the absolute temperature in Kelvin (Bello et al., 2021).

3.2.2 Adsorption Kinetics

Adsorption kinetics pseudo-models, including the pseudo-first-order and pseudo-second-order kinetic models, provide mathematical descriptions of the rate at which molecules or ions are adsorbed onto a solid surface over time. These models are used to analyze and predict the kinetics of adsorption processes and offer insights into how adsorption occurs.

The pseudo-first-order equation is given by

$$\ln\left(Qe - Qt\right) = lnqe - k1t$$

The pseudo-second-order equation is given by

$$\frac{t}{Qt} = \frac{1}{k2Qe^2} + \frac{t}{Qe}$$

where qe is the equilibrium dye concentration of the adsorbent (mg/g), Qt is the quantity adsorbed at any time t, k1 is the pseudo-first-order and k2 is the pseudo-second-order rate constants (Goswami et al., 2022).

The field emission scanning electron microscopy (FESEM) technique was used to analyze the morphology and microstructure of pine-based activated carbon. The porous structure of activated carbon is responsible for the adsorption of various dyes on its surface, as the surface area is directly proportional to the porosity of activated carbon. X-ray diffraction (XRD) was performed to identify the structure of the sample. Energy dispersive X-ray analysis) was performed to identify the elemental composition of the sample. It helps to identify the presence of various elements in activated carbon and helps to decide the different applications it can be used for. Brunauer, Emmett, and Teller (BET) were performed to identify the specific surface area of the sample. Adsorption is dependent on the surface area of the activated carbon: the higher the surface area, the higher its adsorption capacity. Fourier transform infrared spectroscopy (FTIR) was performed at room temperature in the frequency range of 4000 cm^{-1} to 500 cm^{-1} to identify the presence and attachment of functional groups before and after adsorption by activated carbon. Furthermore, the ash content and moisture content were also tested along with the acid-soluble matter.

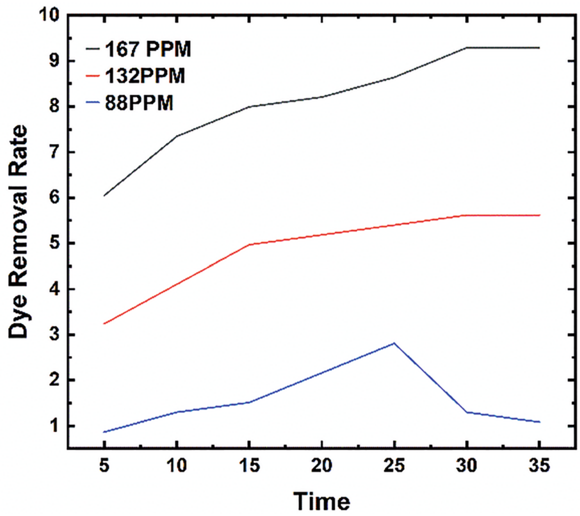

Fig. 1 Dye removal rates at different concentrations using activated carbon

4 Results and Discussion

4.1 Adsorption Study

4.1.1 Effect of Contact Time and Concentration of Solution

Contact time of dye with activated carbon indicate adsorption rate. This study showed that the removal rate of dye increases and then becomes constant after some time. The maximum removal rate of dye for the powdered form of activated carbon was observed between 0 and 30 min, and then it tends to show linear adsorption, as shown in Fig. 1. Furthermore, it was noted that the rate of adsorption of the dye was faster when the solution had a higher concentration compared with the one with a lower base concentration. The adsorption process of dye on pine-based activated carbon appeared to be influenced by the concentration of the adsorbate, particularly in the initial stages. However, it was evident that, regardless of the concentration, the adsorption was most efficient in the initial 20–25 min, with a potential slow-down observed as the concentration decreased.

4.2 Adsorption Isotherm and Kinetics

4.2.1 Adsorption Isotherm

The adsorption isotherm parameters of dye on activated carbon are shown in Table 1, which indicates that the Langmuir is the best-fit isotherm.

Table 1 Adsorption and kinetic model parameters of the adsorption of crystal violet onto pine-based activated carbon

Adsorption Isotherm	Parameter	Values
Langmuir Isotherm	Q_{max}(mg/g)	10
	Kl(L/mg)	0.001
	R_L	0.922
	R^2	0.87241
Freundlich Isotherm	K_f	0.008520204133
	1/n	-0.98243
	R^2	0.78766
Temkin	Bt	1.37883
	At	11.94638903
	R^2	0.6345
Order of Reaction		
Pseudo 1st order	Q_e (mg/g)	4.294134407
	K_1	−0.0001236666667
	R^2	−0.14353
Pseudo 2nd order	Q_e (mg/g)	6.515506906
	K_2	0.1927729003
	R^2	0.99815

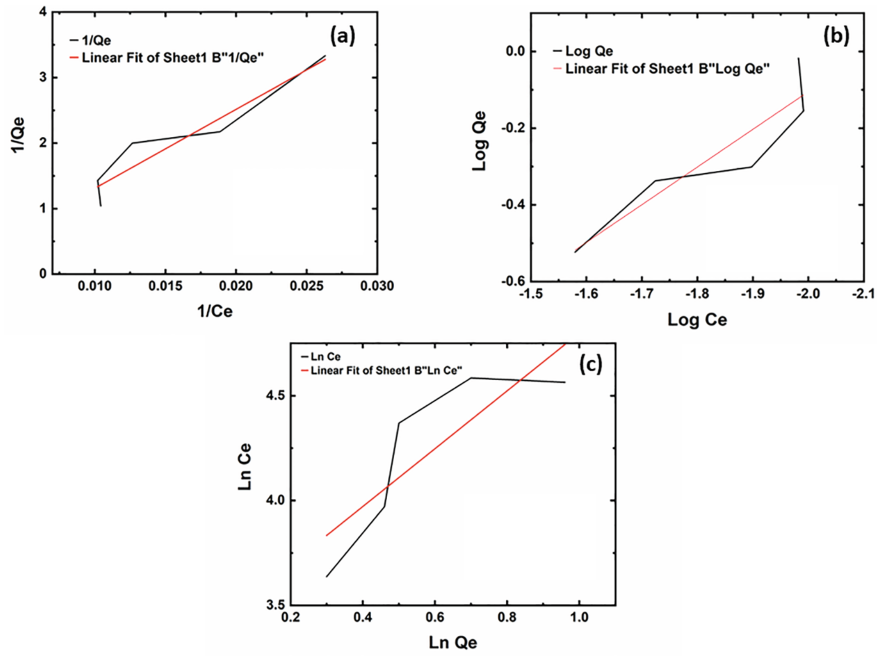

Fig. 2 (**a**) Pseudo-first order and (**b**) pseudo-second order

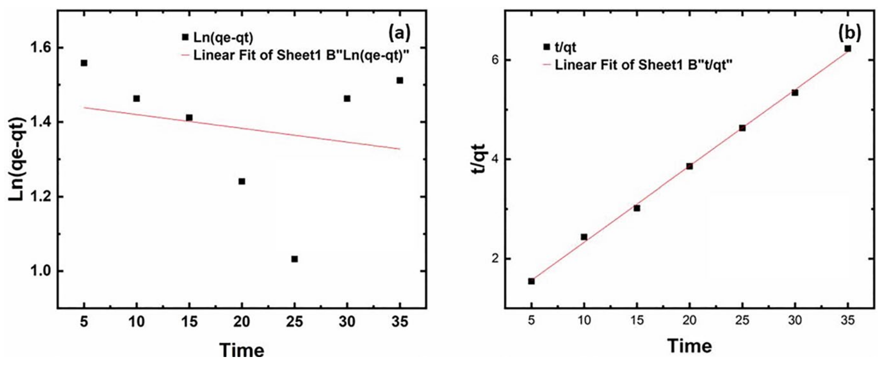

Fig. 3 Isotherm models of the biochar (**a**) Langmuir isotherm, (**b**) Freundlich isotherm, and (**c**) Temkin isotherm

From Table 1, it can be observed that the Langmuir isotherm is the best-fit isotherm due to its linear regression coefficient value of $R^2 = 0.87241$, which is higher than both the Freundlich isotherm ($R^2 = 0.78766$) and the Temkin isotherm ($R^2 = 0.6345$). This also proves the creation of a single layer of adsorbate on the external surface of the adsorbent. The maximum adsorption of dye on the activated carbon was observed to be 10 mg/g. The separation factor (R_L) was 0.922, which is less than 1, demonstrating the presence of adsorption for the process of dye removal.

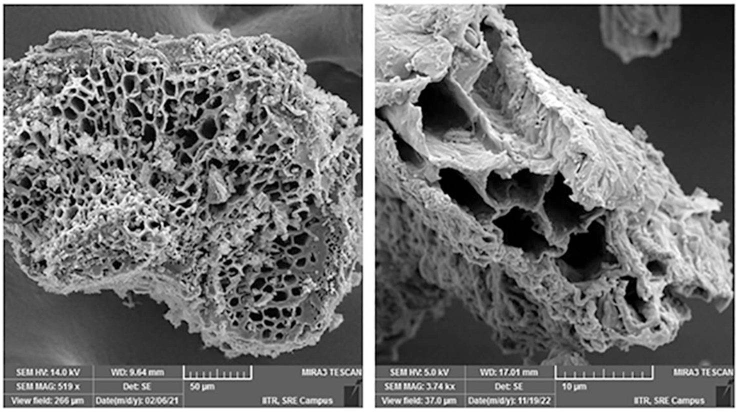

Fig. 4 SEM Images of activated carbon

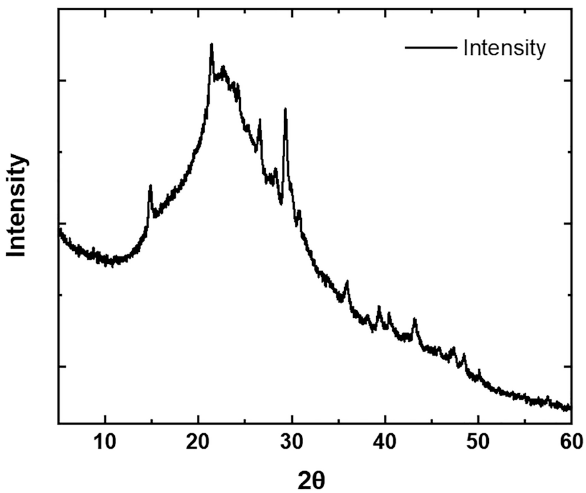

Fig. 5 XRD pattern of the pine-based activated carbon

The value of the empirical parameter (1/n) was calculated to be −0.98243, which is less than 1; hence, cooperative adsorption takes place, which means that favorable adsorption increases with increasing concentration, as shown in Fig. 2. A graphical representation of the isotherms is shown in Fig. 3.

4.2.2 Adsorption Kinetics

The results of the adsorption kinetics study of dye on activated carbon are presented in Table 1, which shows that the kinetic model that best fits is the pseudo-second-order model, as it has a linear regression coefficient value of $R^2 = 0.99815$, which is higher as compared with the pseudo-second-order model ($R^2 = -0.14353$), which proves that the adsorption process is chemical adsorption, resulting in the formation of new bonds, which was also confirmed by the FTIR results. The calculated values of qe were 4.294134407 and 6.515506906 for the pseudo-first order and pseudo-second order, respectively. A graphical representation of the pseudo-first-order and pseudo-second-order reactions is shown in Fig. 2.

4.2.3 SEM

SEM images of the activated carbon made from pine leaves are shown in Fig. 4 (Prasad et al. 2024). It is observed that many cavities were present in activated carbon, which indicates that the material is porous in nature. Porosity is one of the major criteria responsible for adsorption. A network of nanotubes was also observed, which was also responsible for the high porosity and high surface area of the activated carbon. The activated carbon comprises a series of small pores and long tubes, which help increase the adsorption capacity. Activated carbon can be used in various applications, including water filtration, dye removal, and air purification.

4.2.4 XRD

The XRD results of the pine-based activated carbon are shown in Fig. 5. The pattern had a high baseline with a wide peak width in the 2θ range between 15° and 30°, indicating the amorphous structure of the carbon (Boulika et al., 2022). It was also observed that there were peaks located at 2θ = 30°-40° and 40°-50°, which helps to identify the amorphous structure of the activated carbon, as the peaks were formed due to irregularities stacked by carbon rings, which are required for the generation of an adsorption gap (Bakti & Gareso, 2018).

4.2.5 EDAX

EDAX was performed to evaluate the presence of different elements in the activated carbon. From Table 2, it can be observed that the sample contains a large amount of oxygen (51.68%), followed by carbon (19.78%) and magnesium (15.47), with very low amounts of potassium (9.5) and nitrogen(3.57%).

4.2.6 Bet

To determine the specific surface area of the adsorbent, a BET test was performed. The multipoint BET surface area of activated carbon is 65.799 m^2/g. The external surface area is 43.974 m^2/g. The average pore volume and pore radius were 0.024 cc/g and 24.488 Å, respectively, as determined using the BJH adsorption method. The half-pore width was determined to be 9.234 Å. Figure 6 shows the density functional theory pore size distribution (Fig. 7).

Table 2 EDAX results for pine needle-based activated carbon

Element	Weight %	Atomic %
C	19.78	27.4
N	3.57	4.25
O	51.68	53.73
Mg	15.47	10.58
K	9.5	4.04

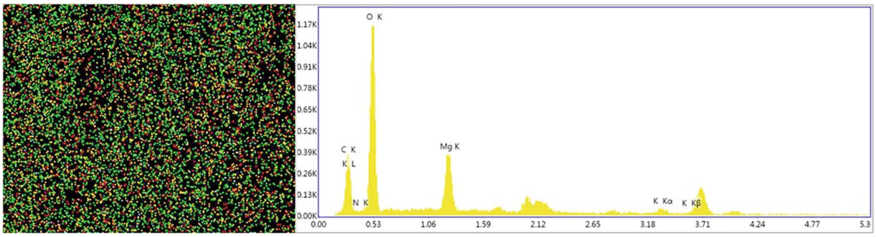

Fig. 6 EDAX of pine-based activated carbon

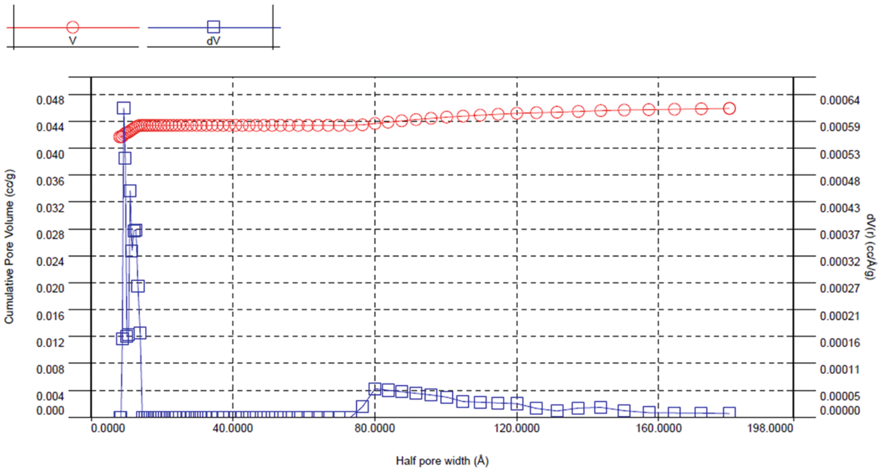

Fig. 7 DFT pore size distribution of the activated carbon

4.2.7 FTIR

The FTIR results of the pine-based activated carbon are shown in Fig. 8. The band at 3673 cm^{-1} indicates OH stretching of free alcohol, and the band at 3440 cm^{-1} indicates the intermolecular bonding of the alcohol OH group. This confirms that the structure formed an alcohol (OH) group during activation at 620°*C*. The band at 3363 cm^{-1} indicates NH stretching. The band at 810 cm^{-1} indicates C=C bending. Hence, the FTIR mentioned the presence of oxygen, nitrogen, and carbon atoms, which was also confirmed by EDAX.

The spectrum of the activated carbon that has adsorbed dye from the wastewater solution collected from the SARA Textiles is shown in Fig. 9. The appearance of numerous new bands indicates the creation of new bonds between the activated carbons, suggesting the occurrence of a chemisorption process. The band at 3699 cm^{-1} indicates OH stretching of free alcohol. The band at 3293 cm^{-1} indicates NH stretching of the primary amine. The band at 3091 cm^{-1} indicates C-H stretching of the alkene. The band at 666 cm^{-1} indicates the stretching of C=C.

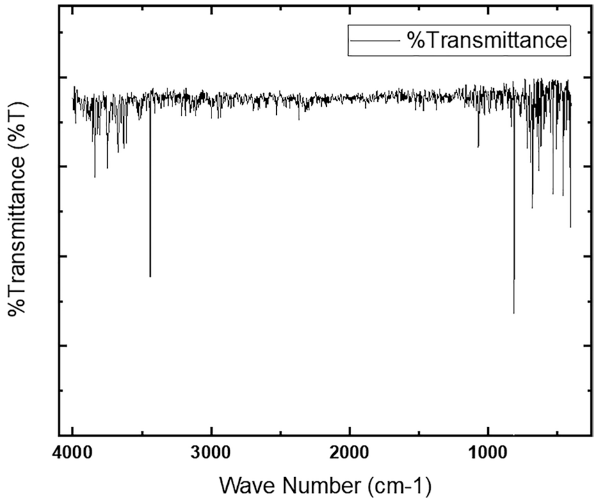

Fig. 8 FTIR of activated carbon

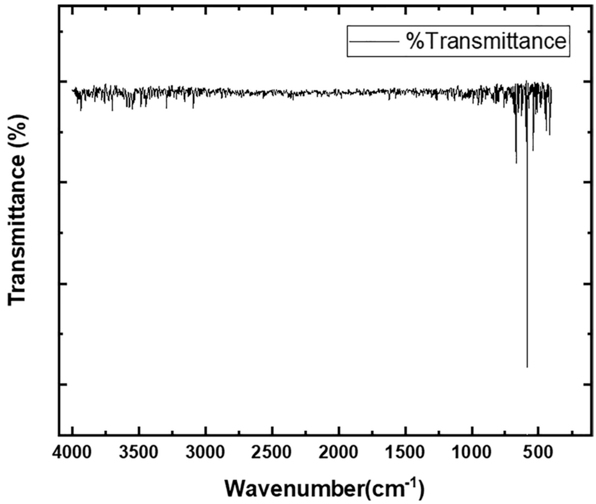

Fig. 9 FTIR of activated carbon after adsorbing dye from the SARA Textile solution

4.2.8 Ash Content

Ash content refers to the residue of the precursor material after it is carbonized (Yakout et al., 2015). The ash content of the pine-based activated carbon carbonized at $620°C$ was observed to be 6.04%. The concentration of ash in the solid products is influenced by the degree of carbonization and the chemical composition of the raw materials, primarily consisting of inorganic compounds.

4.2.9 Moisture Content

The moisture content may not directly impact the performance of the adsorbent in wastewater treatment; it has the potential to dilute activated carbon. To counteract this dilution effect, a higher quantity of activated carbon may be required to achieve the desired results. In the case of the pine-based activated carbon carbonized at 620 °C, the observed moisture content was 8.33%, possibly attributed to the adsorption of moisture from the air.

5 Conclusion

In this study, pine-based activated carbon was prepared at 620 $°C$ and tested for adsorption by a crystal violet dye solution, which was acquired from the textile Industry. A porous structure was observed, which helped to attain a high surface area, resulting in good adsorption capacity. The Langmuir model was the best-fit model for the adsorption of malachite green on pine-based activated carbon, indicating monolayer formation, and showed a maximum adsorption capacity of 10 mg/g. The pseudo-second-order reaction is best suited to the adsorption process, with a Qe value of 6.515506906 mg/g, indicating the chemical adsorption to take place, which was also confirmed by FTIR spectroscopy. The amorphous structure of the activated carbon was confirmed by the XRD results, and BET confirmed that the surface area of the activated carbon was 103.360 m^2/g. The ash content and moisture content of the activated carbon were calculated to be 6.04% and 8.33%, respectively.

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