frontiers | Frontiers in Sustainable Cities

TYPE Review
PUBLISHED 11 January 2024
DOI 10.3389/frsc.2023.1308684

Check for updates

OPEN ACCESS

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RECEIVED 06 October 2023
ACCEPTED 24 November 2023
PUBLISHED 11 January 2024

CITATION
Hussain S, Hussain E, Saxena P, Sharma A, Thathola P and Sonwani S (2024) Navigating the impact of climate change in India: a perspective on climate action (SDG13) and sustainable cities and communities (SDG11). *Front. Sustain. Cities* 5:1308684. doi: 10.3389/frsc.2023.1308684

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Navigating the impact of climate change in India: a perspective on climate action (SDG13) and sustainable cities and communities (SDG11)

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Climate change is a global concern of the current century. Its rapid escalation and ever-increasing intensity have been felt worldwide, leading to dramatic impacts globally. The aftermath of climate change in India has brought about a profound transformation in India's environmental, socio-economic, and urban landscapes. In 2019, India ranked seventh, among the most affected countries by extreme weather events caused due to changing climate. This impact was evident in terms of both, the human toll with 2,267 lives lost, and the economic damage, which accounted for 66,182 million US$ Purchasing power parities (PPPs). Over the recent years, India has experienced a significant increase in the number and frequency of extreme weather events, causing vulnerable communities. The country experienced severe air pollution problems in several metropolitan cities and was highlighted in the list of the world's most polluted cities. Additionally, India has become the most populous nation globally, boasting a population of 1.4 billion people, equating to ∼18% of the global population, and experiencing an increased rate of consumption of natural resources. Owing to the country's current scenario, various climate mitigation strategies, including nature-based solutions, must be implemented to reduce such impacts and support India's target of achieving the Sustainable Development Goals (SDGs). This review tries to have a holistic understanding of the effects of climate change on different sectors to identify India's challenges in achieving SDG 13 and SDG 11. Finally, it also highlighted the future recommendations for climate change-related research from an Indian perspective.

KEYWORDS

urbanization and development, climate change, human health, sustainable development, India

1 Introduction

India, with its diverse geography, dense population, and intricate socio-economic fabric, is particularly susceptible to the changing climate. Notably, the issue of air pollution has become a prominent concern in India, further compounded by the effects of climate change. Air pollution in India is fueled by diverse sources, including industrial emissions, vehicular pollution, biomass burning, and dust particles (Sahu and Saxena, 2015; Sonwani, 2016; Sonwani et al., 2021a,b,c, 2022a; Hussain and Hoque, 2022b). As per the World Air Quality Report State of Global Air (SoGA), many booming cities in India rank among the top 15 most polluted cities of the world viz. Delhi (1st rank), Kolkata (2nd rank) and Mumbai (14th rank).

The county has severe air pollution that triggers climate change and vice-versa. Air pollution and climate change, are closely intertwined (Singh and Yadav, 2021; Sonwani et al., 2022b). Matyssek et al. (2012), described air pollution as a component of climate change. Anthropogenic emissions play a significant role in causing both air pollution and climate change. In addition to the greenhouse gases (GHGs) such as—carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs) and Tropospheric ozone (O_3), air pollutants such as black carbon (BC), brown carbon (BrC) and aerosol also having significant impact on climate (Ramanathan and Carmichael, 2008; Sonwani et al., 2021a,b,c, 2022a). Apart from the direct climate impact of rising ground-level ozone, it also indirectly affects the lifespan of other GHGs like methane and causes additional climate impact (Singh and Yadav, 2021). Conversely, climate change influences ozone concentrations through both dynamic and chemical changes in the atmosphere. Moreover, the rising earth's surface temperature causes glaciers' melting and sublimation, causing resulting in more atmospheric water vapor, additionally participating in secondary air pollutant formation causing ecological damage (Saxena and Sonwani, 2019a). Thus, we have scientific evidence which proves that air pollution and climate change together impact the composition of the atmosphere and are responsible for environmental damage.

Climate change is an unprecedented global challenge that has far-reaching consequences for countries around the world (Klingenfeld and Schellnhuber, 2012; Haibach and Schneider, 2013). The aftermath of climate change in India manifests in various forms, including rising temperatures (Krishnan et al., 2020), altered precipitation patterns (Behera et al., 2019; Sonwani and Kulshrestha, 2019), increased regularity and strength of severe weather occurrences (Hussain and Hoque, 2022a; Saxena et al., 2022); sea-level rise (Krishnan et al., 2020), instance and frequent forest fire incidences (Jain et al., 2021), sever dust storm incidences and draft (Maji and Sonwani, 2022). These impacts permeate critical sectors including agriculture, water resources, public health and biodiversity.

The pervasive effects of climate change in India span across multiple sectors, posing significant obstacles to achieving Sustainable Development Goal 13 (SDG 13) - Climate Action. The bad air quality with changing climate exacerbates one another issue, which is variable atmospheric composition (D'Amato et al., 2002). This not only poses significant risks to respiratory illnesses and cardiovascular diseases (Ravindra et al., 2019; Goel et al., 2021; Sonwani et al., 2022a), but also impairs agricultural productivity (Wiebe et al., 2019), economic loss (Sathaye et al., 2006; Saurabh Sonwani and Vandana Maurya, 2019; Parikh and Bhavsar, 2023) disrupts vegetation and ecosystems, and hampers sustainable development (Sonwani et al., 2022b). The Climate India 2022 report by the Center for Science and Environment (CSE) highlighted that India recorded weather extremes on 22 out of 273 days between January to September 2022 (Climate India, 2022).

Tackling the aftermath of climate change and addressing air pollution necessitates a comprehensive and interdisciplinary approach. Achieving SDG 13 requires adopting efficient strategies to minimize the release of greenhouse gases, smart agricultural practices, promoting renewable energy sources, and enhancing energy efficiency. Also, implementing adaptation strategies, green infrastructure, and environmentally sustainable and socially resilient cities, and efficient waste management approaches are crucial for SDG 11 to minimize the climate change impact (Zakaria et al., 2020). Moreover, sustainable water management (Xiang et al., 2021), air and watershed management and enhancing disaster preparedness with early warning system are also useful to combat changing climate (Saxena and Sonwani, 2020; Hussain and Hoque, 2022a).

The objective of this review is to highlight the current status and menace of air pollution and climate change and their pervasive effects in India. It also explores the potential solutions and related challenges to achieve SDG 13 (*Climate action*) with special reference to climate change adaptation and mitigation strategies. Furthermore, the impact of the changing climate on SDG 11 (S*ustainable Cities and Communities*) was also highlighted in reference to sustainable infrastructure and healthy well-being in the Indian context. A flow diagram summarizing the adverse effects of climate change, and possible strategies for achieving the targeted sustainable development goal has been presented in Figure 1. This review makes an effort to have a holistic understanding of the effects of climate change (extreme events, warming, etc.) on different sectors (agriculture, health, and communities) so as to identify India's challenges in achieving SDG 13 and SDG 11.

2 Status of climate change in India

The susceptibility of developing countries to the consequences of climate change in comparison to developed countries is now widely recognized. This is due to the fragile ecological environments, high risk to economic systems, and low-income levels of the majority of citizens which limit the ability to adapt (Panda, 2009). The rapid urbanization, alterations in river patterns, the impact of shifting cultivation practices, the spread of erosion, and the progression of desertification are resulting in significant changes in land use. These changes in land use have a direct correlation with the hydrological cycle, as noted by Sreenivasulu and Bhaskar (2010), and they play a pivotal role in causing extensive transformations within associated ecosystems, as highlighted by Chakraborty (2009). Developing countries, such as China and India collectively contribute a significant share of global carbon dioxide (CO_2) and GHG emissions, mainly due to their growing populations and industrialization (Ahmed et al., 2022; Pathak, 2023). Between 1970 and 2021, India experienced a total of 573 disasters related to extreme weather, climate, and water events, resulting in the loss of 138,377 lives, as reported by the Indian Meteorological Department (IMD Annual Report, 2021). India has experienced the highest temperatures

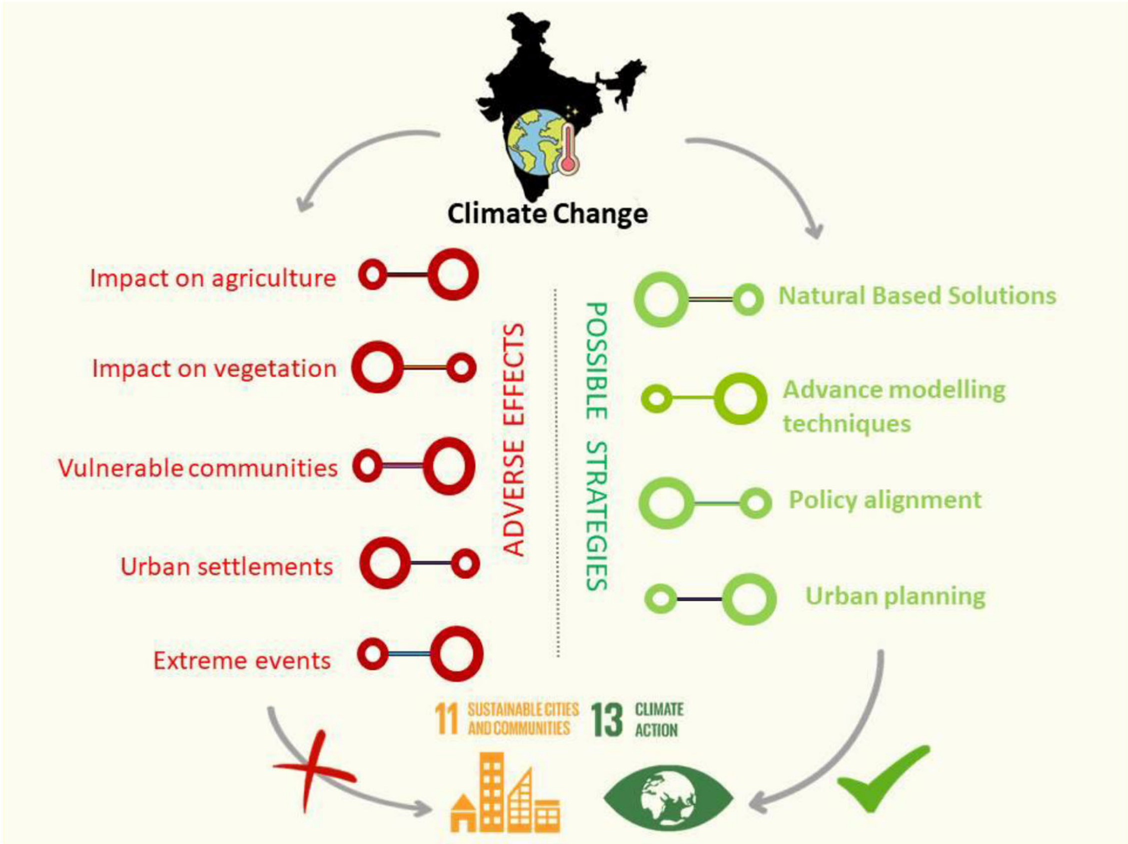

FIGURE 1
A schematic representation summarizing the adverse effects of climate change and possible strategies to achieve the selected sustainable goals.

and the most prolonged dry spells ever recorded in recent years (Panda et al., 2017) and is now listed in the UN's Global Drought Vulnerability Index with consecutive drought episodes occurring in the major rice-producing states such as UP, Bihar, Jharkhand, and West Bengal (Amrit et al., 2021). Simultaneously, frequent episodes of intense, short-lived downpours resulting in flooding incidents, such as the deluge in Uttarakhand in the year 2013, Kashmir in the year 2014, Kerala in 2018 etc. have been reported (Akram et al., 2023). Recently, India has become the most populous nation globally boasting a population of 1.4 billion people, equating to 17.7% of the global population (Salunke, 2022) which would lead to an increasing carbon footprint. According to a study by Chaturvedi et al. (2012), the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble mean climate results for India in the *business-as-usual (RCP6.0–RCP8.5) scenario*, the mean warming was predicted to be between 1.7–2°C by 2030 and 3.3–4.8°C by 2080 in comparison to pre-industrial times. Whereas, *under the business-as-usual scenario*, all-India precipitation is predicted to increase from 4% to 5% by 2030 and from 6%−14% toward the end of the century (2080s).

Due to rapid economic and developmental growth, India is experiencing sector-specific CO_2 emissions from four major sectors Electricity (35.05%), Agriculture (23.18%), Construction/Manufacture (15.92%), and Transport (8.64%) (Tiseo, 2023a). While per capita CO_2 emissions in India were relatively low at 1.82 metric tons and significantly below the global average of 4.55 metric tons (World Bank, 2021), the country ranked as the fourth-largest emitter in 2017 due to its substantial population and economic size (UNEP, 2019). Per capita CO_2 emissions in India have shown an increasing trend, rising from 0.39 metric tons in 1970 to a peak of 1.91 metric tons in 2022 (Tiseo, 2023b). Furthermore, carbon dioxide emissions stemming from the use of fossil fuels and industrial activities in India surged by 6.5% in 2022, setting a new record at 2.7 billion metric tons ($GtCO_2$) (Tiseo, 2023c). In terms of annual anthropogenic emissions, India is estimated to release 47,000 million metric tons of CO_2, 570 million metric tons of CCl_4, and 9 million metric tons of N_2O (Basha and Reddy, 2022). Emissions of a few pollutants in India were estimated to be 2.144 tons/capita of GHG emissions, 69.4 kg/capita of CO emission, 20.36 kg/capita of NOx emission, and 9.51 kg/capita of SOx emission (OECD, 2023). Additionally, climate change-led disasters like forest fires add more concentration to the pollutants. Each year, the world sees ∼4.3–5.5 $GtCO_2$ e/year emissions caused by changes in land use and land cover (Sannigrahi et al., 2020). Between 2003 and 2017, a significant number of 520,861 forest fires were identified across the diverse

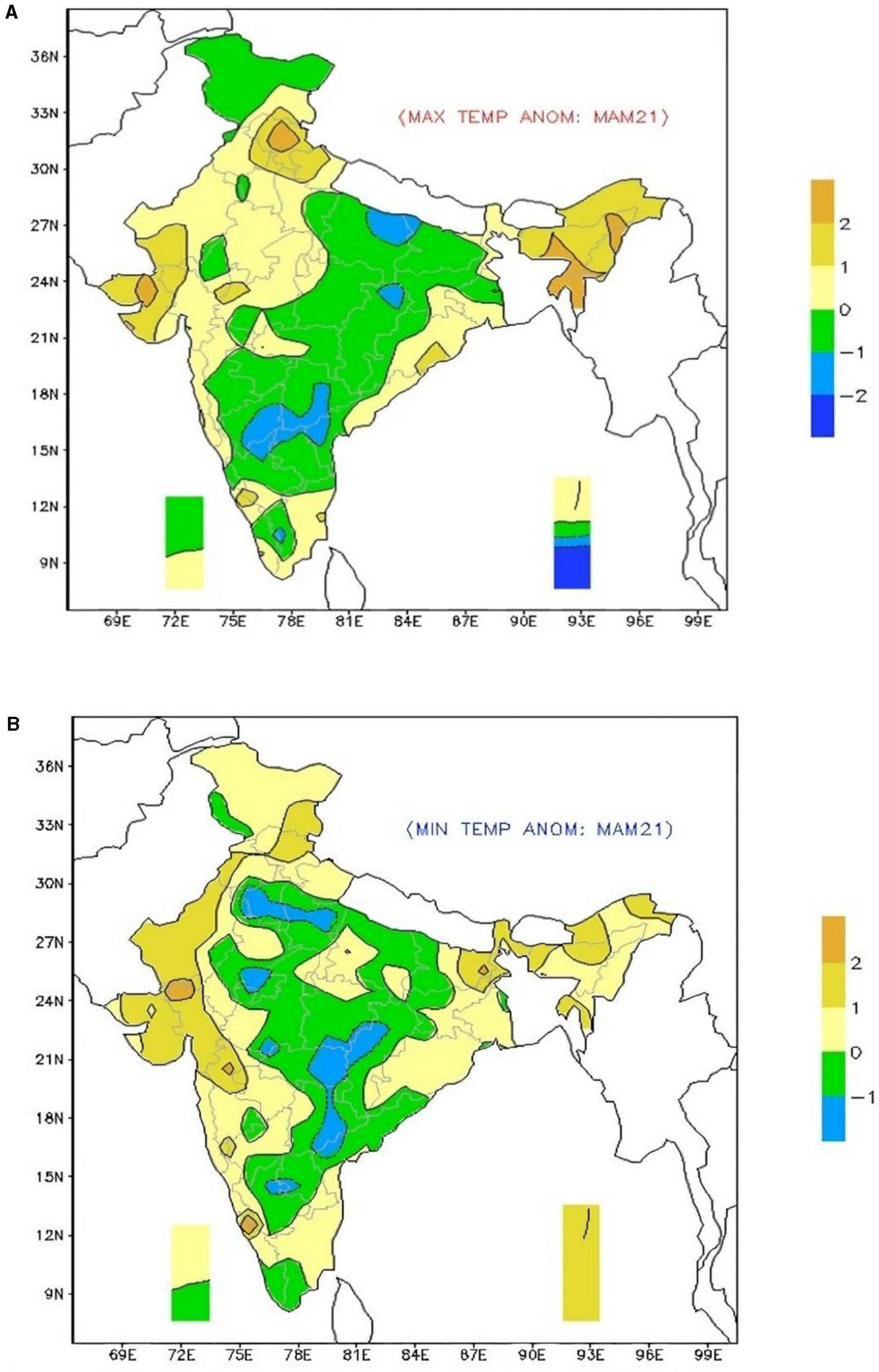

FIGURE 2
Mean seasonal temperature anomalies (°C) **(A)** maximum **(B)** minimum (source: IMD Annual Report, 2021).

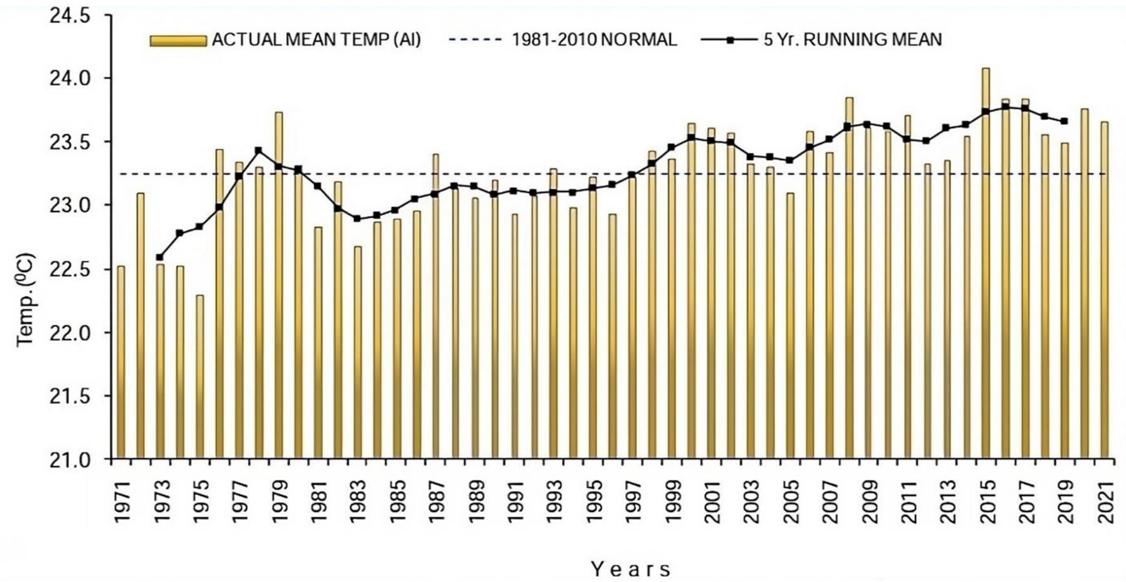

FIGURE 3
Time series of mean temperature averaged over India (vertical bars) and 5 year running mean (continuous line) for the post monsoon season (1971–2021) (source: IMD Annual Report, 2021).

forest landscapes of India (Sannigrahi et al., 2020). For instance, the Uttarakhand Forest fire caused an increase of 52% in CO, 52% in NOx, and 11% in O_3 during the High Fire Activity Period (HFAP).

2.1 Temperature and rainfall anomaly

The mean temperature across India in 2021 averaged 21.43°C, ranking as the third-highest on record since 1901, following the years 2016 (21.8°C) and 2009 (21.59°C) (IMD Annual Report, 2021). In Figures 2A, B, we can observe the deviations from the average seasonal maximum and minimum temperatures. Figure 3 highlighted the time series of average mean temperature for the post monsoon season, over India for a period from 1971–2021. Over most regions of the country, the maximum temperature exceeded the normal values, with exceptions in certain areas of northwest India, eastern and northeastern India, central India and southern peninsular India. Particularly in some areas, such as Assam and Meghalaya, Nagaland, Manipur, Mizoram, Tripura, Himachal Pradesh and Saurashtra and Kutch, experienced maximum temperature anomalies exceeding 2°C. Similarly, when looking at the minimum temperatures, they were generally higher than the typical values for most parts of the country, except for specific regions in northwest India, central India, southern peninsular India, and Lakshadweep. Notably, some areas, including northern Saurashtra and Kutch, central Maharashtra, Bihar, North Interior Karnataka, and southern Kerala and Mahe, witnessed minimum temperature anomalies surpassing 2°C. Conversely, certain areas like Delhi, West Uttar Pradesh, Haryana, Chandigarh, East Rajasthan, southern Madhya Pradesh, Chhattisgarh, Vidarbha, Andhra Pradesh, Telangana, and South Interior Karnataka experienced minimum temperature anomalies lower than −1°C (IMD Annual Report, 2021). There has been visible evidence of altered precipitation patterns over the country. In some regions of Tamil Nadu, Puducherry, Karaikal, Kerala, Mahe, and Lakshadweep, the rainfall anomaly exceeded 100 mm. Conversely, there were areas in Arunachal Pradesh, Assam, Meghalaya, Uttarakhand, Punjab, Himachal Pradesh, and the western parts of Jammu and Kashmir and Ladakh where the negative rainfall anomaly was greater than 50 mm. Furthermore, in parts of Arunachal Pradesh, Uttarakhand, Punjab, Himachal Pradesh, and Jammu and Kashmir, the negative rainfall anomaly exceeded 75 mm (Figures 4, 5).

2.2 Climate change transitions and projections against climate variables in India

Figure 6 shows India's transitions in relation to climate change. It mentioned the different initiatives related to the summits, agreements, rectifications, national action plans, and launch and amendments of any acts relevant to climate change and mitigation.

The repercussions of climate change, encompassing escalating temperatures, acidification of oceans, and rising sea levels, have yielded adverse consequences for both essential services and the livelihoods of those reliant upon them. Since the 20th century, Asia has witnessed a consistent rise in surface air temperatures, resulting in significant concerns for social and economic stability (Ren et al., 2023). This triggers an increased likelihood of heat waves, alterations of the monsoon patterns, frequent flood occurrences

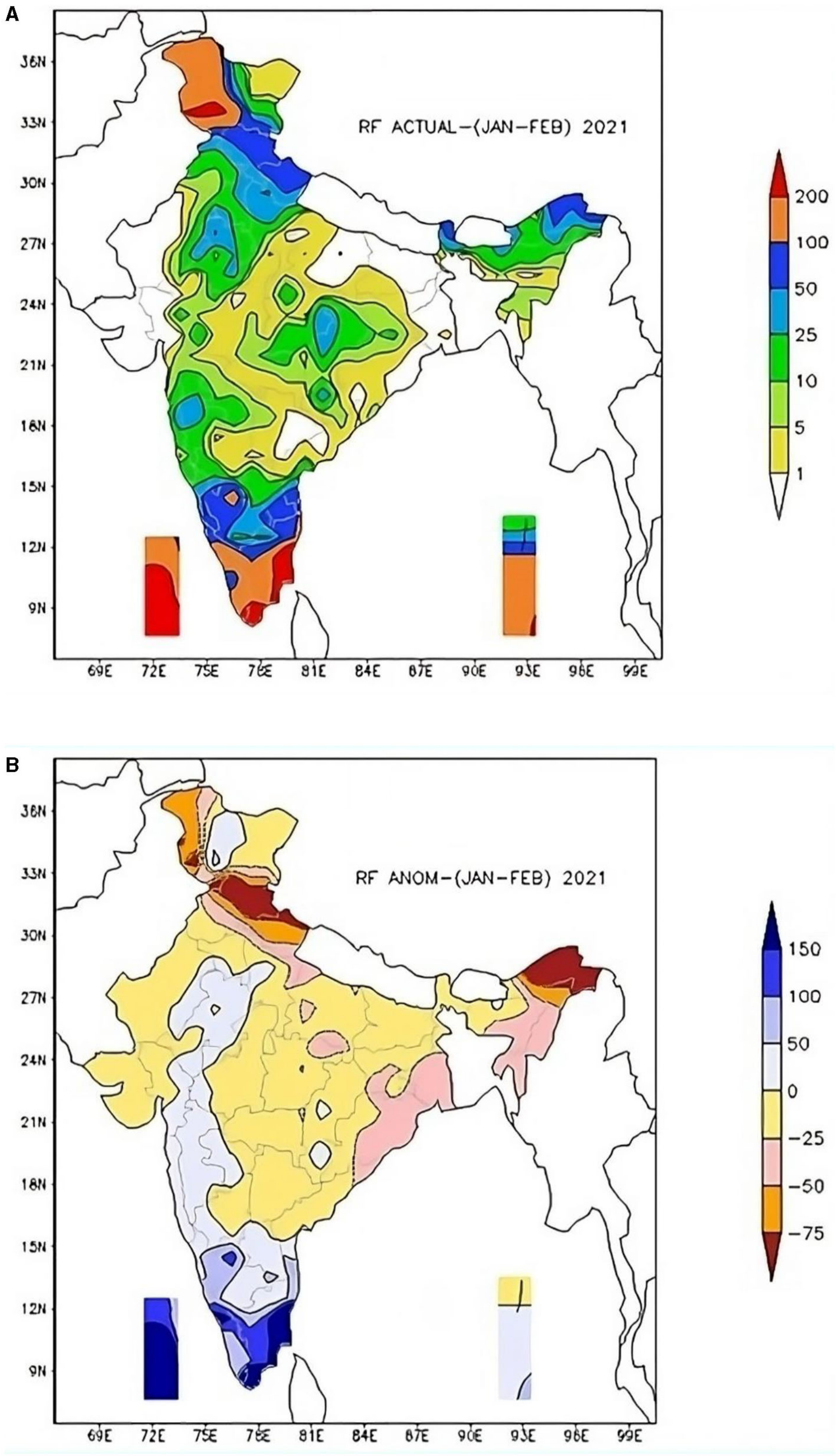

FIGURE 4
Spatial pattern of **(A)** seasonal rainfall winter (January–February) **(B)** seasonal rainfall anomaly (mm) (source: IMD Annual Report, 2021).

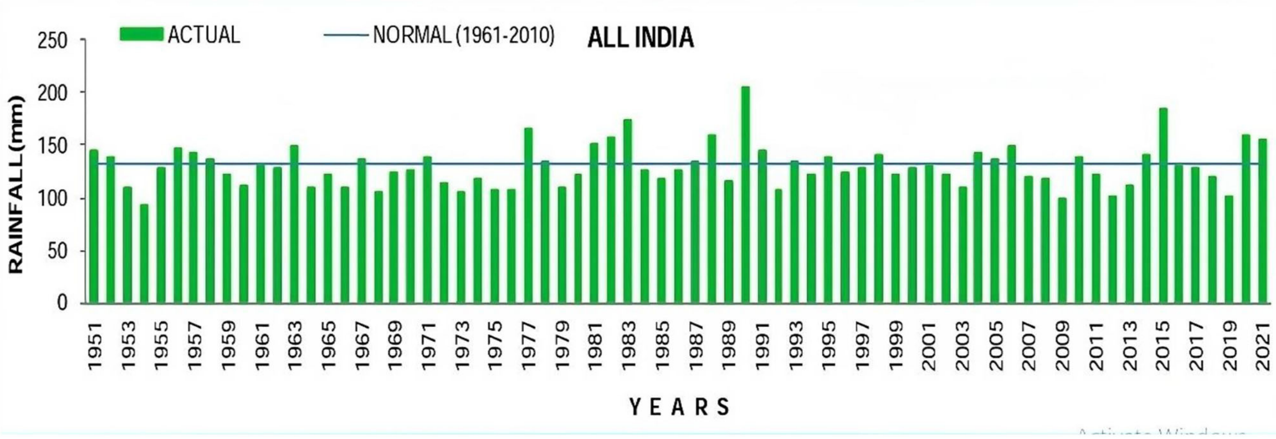

FIGURE 5
Seasonal rainfall over the country as a whole for the period 1951–2021 (source: IMD Annual Report, 2021).

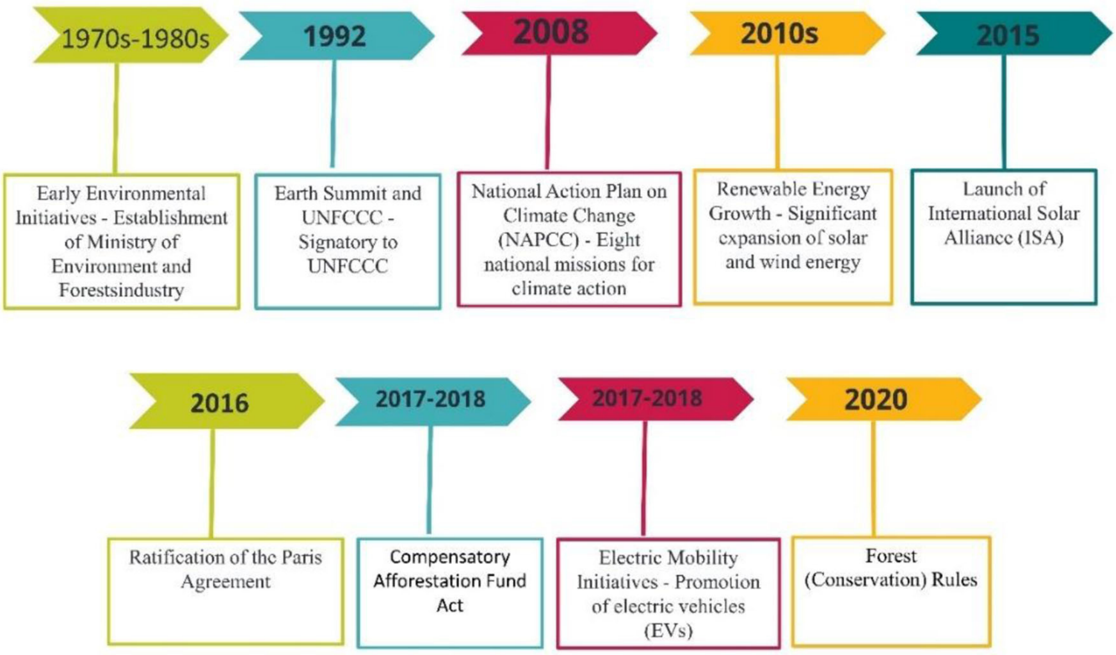

FIGURE 6
Schematic diagram of timeline for India's transition in climate change.

in regions experiencing monsoons, and the melting of glaciers in the Hindu Kush Himalaya area (United Nations Environment Programme, 2009).

India, as a developing nation, contributes to around 3.2% of the total global Gross Domestic Product (GDP). It's worth noting that India is home to nearly 17.7% of the world's population and is responsible for ~6.8% of the world's carbon emissions, placing it fifth in terms of geopolitical risk rankings (Adebayo et al., 2023). Significantly, a 10% increase in Economic Policy Uncertainty in India could have adverse effects on the economy, potentially hindering the green economy by reducing it by 0.535% (Liang and Qamruzzaman, 2022). The danger of irreversible loss extends to vital marine and coastal ecosystems, including coral reefs, tidal marshes, seagrass meadows, and plankton communities (UN, 2022). Meanwhile, mangroves in India remain under continuous threat from pollution, conversion for aquaculture and agriculture, as well as challenges related to climate such as sea level rise and coastal erosion (Akram et al., 2023). These risks also drastically intensify, for example, global warming exceeds a 2°C rise in temperature and calls for fluctuations in the climate system. In India, the hotter summer climate has led to a surge in demand for cooling, compounding the situation due to rapid population growth (Hoegh-Guldberg et al., 2018). These climatic factors have introduced water stress affecting both water supply and demand. Scarce precipitation further impacts water supply demands, prompting the increased use of energy-intensive techniques like desalination and underground water pumping (IPCC, 2023).

Transboundary river basins like the Indus and Ganges in the mid-21st century are predicted to face severe water scarcity. India, in particular, faces an elevated risk of experiencing increased drought conditions ranging from 5% to 20% by the close of this century (IPCC, 2023). Additionally, the security of local and downstream communities is threatened by Glacier Lake Outburst Floods (GLOFs). Moreover, the persistence of rising temperatures, shifting precipitation patterns, and climate extremes such as heat waves, droughts, and typhoons will maintain their role as pivotal vulnerability factors, significantly shaping agricultural productivity in Asia (IPCC, 2023). Projections for the agricultural and food industry include notable declines in fisheries, aquaculture, and agriculture yield, specifically in South Asia. In India, rice production may decline by 10%−30% and maize production by 25%−70%, considering a temperature increase in the range of 1°C−4°C. In this context, Krishnan et al. (2020) published a report by the Ministry of Earth Sciences (MoES), Government of India where past and projected changes in the country due to climate change have been discussed in detail (Table 1).

3 Climate change impacts

3.1 Impact on forest

Climate change exerts an impact on various natural disruptions that jeopardize the wellbeing of forests. These encompass insect infestations, the intrusion of non-native species, wildfires, and severe storms. Certain disturbances, such as wildfires, occur abruptly. The consequences of climate change on forests carry significant implications for those individuals whose livelihoods rely on forest resources. India, being a mega-biodiversity nation, dedicates over one-fifth of its land to forests. In a country with almost 173,000 villages designated as forest villages, there is a substantial reliance of communities on these forest resources (Gopalakrishnan et al., 2011). The effects of climate change on India's vegetation are region-specific. For instance, the Himalayan region is particularly vulnerable to the loss of alpine meadows and the upward shift of tree-line due to rising temperatures (Manish et al., 2016). The coastal mangrove forests of India also face detrimental effects, including increased saltwater intrusion and decreased productivity, due to the effects of climate change (Semba et al., 2022).

Climate plays a pivotal role in shaping vegetation patterns on a global scale and exerts a substantial impact on the arrangement, composition, and ecological dynamics of forests (Kirschbaum et al., 1996). The 2022 IUFRO hybrid meeting held in Vienna, Austria was themed "Forests in a Volatile World—Global Collaboration to Sustain Forests and Their Societal Benefits". The annual report evaluates the world's progress in minimizing emissions from deforestation and deterioration of forested areas. (REDD+) and was prepared by IUFRO's Global Forest Expert Panels (GFEP) Programme (this full line should be deleted). A key takeaway from their report is that although REDD+ has served as a convenient framework for various activities focused on curbing deforestation and forest degradation, the intricate complexities between forests, land use, and climate still remain an issue (IUFRO Report, 2020). In a warmer world, the forests currently play a vital role as carbon sinks and could be entirely eroded. Land ecosystems may transition from being a net carbon dioxide absorber to becoming a significant source of carbon dioxide emissions (Seppälä et al., 2009).

In India, air pollution and climate change have profound effects on vegetation, posing significant challenges to the country's ecosystems and terrestrial productivity. Air pollutants can harm the health of trees, leading to leaf discoloration, reduced growth, and even tree mortality. Climate change-induced factors like rising temperatures and alterations in rainfall distribution, and altered pest and disease dynamics further stress forest ecosystems, potentially leading to forest decline and loss of biodiversity (Saxena and Sonwani, 2019b; Saxena and Srivastava, 2020; Sonwani and Saxena, 2022; Sonwani and Shukla, 2022; Sonwani et al., 2022a).

According to a study by Chaturvedi et al. (2011), which utilized the Regional Climate Model of the Hadley Center (HadRM3) and the dynamic global vegetation model IBIS, projections were made for climate change scenarios. The study highlights that the upper Himalayas, northern and central areas of the Western Ghats, and certain regions of central India are particularly susceptible to the expected effects of climate change. On the other hand, the assessment suggests that the forests in the northeastern part of India exhibit better capacity to adapt or withstand the projected changes in climate.

One of the notable impacts of climate change on vegetation is the shifting distribution and composition of plant species. As temperatures increase, certain plants may struggle to survive in their existing habitats and gradually migrate to more suitable regions (Chauhan et al., 2022). This phenomenon, known as "shifting vegetation belts", Has the potential to result in alterations in the functioning of ecosystems, affecting the interactions between plants, animals, and their environment (Sonwani et al., 2022a). Another evident impact is the alteration of phenological patterns in plants (Corlett and Lafrankie, 1998; Workie and Debella, 2018) such as changes in flowering and fruiting seasons. Climate change-derived shifts in temperature and rainfall patterns can disrupt the synchronicity among plants and their pollinating or seed-dispersing agents, potentially leading to mismatches in these critical ecological relationships. Additionally, the study conducted by Ranjan and Gorai (2022) examined the start-of-season (SOS) and end-of-season (EOS) trends for various vegetation types. During the period of 2001–2010, most vegetation types (excluding winter snow vegetation and mixed forest) exhibited a delay in both SOS and EOS. The delay occurred at a rate ranging from 0.009 to 0.29 days per year for SOS and 0.03 to 0.33 days per year for EOS. Conversely, from 2010 to 2019, the EOS and SOS of all vegetation types (except mixed forest) displayed an advancing trend. The SOS advanced at a rate of 0.06 to 0.24 days per year, while the EOS preponed at a rate of 0.17–0.23 days per year. These findings indicate significant changes in the timing of the period of growth for various types of vegetation. Such alterations can have implications for plant growth, phenology, and ecosystem dynamics (Shrestha, 2019). Furthermore, climate change

TABLE 1 Table listing projected changes against different climate variables in India (adapted from Krishnan et al., 2020).

S.No.	Climate variables	Projected changes
1.	Warming over India	Toward the end of the 21st century, it is anticipated that the average temperature increase across India will fall within the scope of 2.4–4.4°C, encompassing various scenarios of greenhouse gas-induced warming.
2.	Warming over Indian ocean	The average sea surface temperature (SST) in the tropical Indian Ocean has escalated by 1°C between 1951 and 2015, and predictions indicate a continued rise throughout the 21st century.
3.	Monsoon precipitation	As temperatures and atmospheric humidity levels increase, climate models predict a significant uptick in the average, extreme, and yearly fluctuations of monsoon showers by the close of the century (Kitoh, 2017).
4.	Sea-level rise in the North Indian Ocean	In the North Indian Ocean, sea-level rise has been primarily driven by thermal expansion and monsoon winds (IPCC AR5).
5.	Droughts and floods	In a warming global climate, increased rates of glaciers and snowmelt would amplify the flow of streams and exacerbate the potential for flooding across the river basins of the Himalayas. The Indus, Ganga, and Brahmaputra basins, in particular, are expected to face a heightened risk of intensified flooding in the coming years if additional measures for adaptation and risk reduction are not implemented (Lutz etale, 2014).
6.	Tropical cyclonic storms	As global warming persists, the occurrence of highly intense cyclonic storms (VSCS) in the North Indian Ocean is anticipated to rise even more throughout the 21st century.
7.	Himalayan cryosphere	As warming persists, climate projections indicate an ongoing reduction in snowfall across the Hindu Kush Himalaya (HKH) region throughout the 21st century.

threatens the overall productivity and health of vegetation in India (Upgupta et al., 2015; Ahmad et al., 2018). Increased heat waves and droughts can induce water stress on plants (Marchin et al., 2022), impacting their growth, productivity, and survival. Additionally, rising temperatures generate a conducive environment for the rapid increase of pests and diseases (Shrestha, 2019; Zayan, 2019), further endangering the health and resilience of plant populations.

The study by Haughan et al. (2022) on the impact of climate change on Indian forests reveals a significant rise in annual forest loss during the 17-year period from 2001 to 2018, with the Northeast region experiencing the highest proportion of this loss. This increase in forest loss is attributed to changing trends in temperature and precipitation over time. Their study raises concern about climate velocities recorded in the country, reaching 97 km/year. They underscore the importance of comprehending the unique regional and seasonal connections between climatic conditions and forest distribution to effectively conserve the remaining forests as climate change continues to accelerate.

3.2 Impact on agriculture

Agriculture, being a vast sector highly sensitive to weather conditions, is particularly vulnerable to the impacts of climate change, resulting in significant economic consequences. Variations in climatic factors like temperature and rainfall have a profound effect on crop yields. The influence of rising temperatures, changes in precipitation, and increased CO_2 levels vary depending on the specific crop, location, and the extent of these alterations (Malhi et al., 2021). Additionally, regions with higher humidity and warmer climates tend to face greater challenges from insect pests and diseases (Malhi et al., 2021). To meet the food and nutritional demands of the global population by 2050, it is imperative to achieve a 60% increase in worldwide agricultural production from 2005/2007 levels, with developing countries aiming for a 77% increase and developed nations targeting a 24% rise (Alexandratos and Bruinsma, 2012). Any loss in crop yields can potentially drive up food prices and have a substantial impact on global agricultural well-being, potentially resulting in a 0.3% annual decrease in global GDP by 2100 (Stevanovic et al., 2016). Recent evidence suggests that approximately 9% of cropland expansion in developing countries over the last two decades can be attributed to dry anomalies, as farmers expand their agricultural areas to compensate for yield losses (Zaveri et al., 2020).

Guntukula (2020) conducted an analysis using annual time-series data spanning 58 years (1961–2017) to examine the impact of climatic variables, specifically rainfall, maximum temperature, and minimum temperature, on the yields of seven major crops in the region viz. rice, wheat, pulses, rapeseeds and mustard, cotton, sugarcane, and groundnut in India. The study observed that rainfall, and maximum and minimum temperatures, have a substantial effect on crop productivity. The specific impact of these variables varied across different crops and regions. A sensitivity analysis using CERES (crop estimation through resources and environmental synthesis) has also shown that wheat and rice yields in northwest India have the potential to increase by 28% and 15%, respectively, at double the levels of CO_2; however, the increased thermal stress due to elevated level of temperatures associated with high CO_2 nearly cancels out the positive impact (Malhi et al., 2021).

India has already witnessed adverse impacts from recent climate patterns, which are attributed to emissions on a worldwide scale of both long-lived greenhouse gases (LLGHGs) and other short-lived climate pollutants (SLCPs) particularly, tropospheric ozone and black carbon (Burney and Ramanathan, 2014). These pollutants not only have indirect effects on crop yields through climate changes but also exert direct effects. Burney and Ramanathan (2014) investigated the combined effects of climate change, the direct consequences of short-lived climate pollutants (SLCPs), and air pollutants on wheat and rice crop yields in India spanning the years from 1980 to 2010. Their statistical model revealed that, on average across the country, wheat yields and rice yields in 2010 were up to 36% and 20% lower respectively, than in a scenario where climate change had not occurred. Remarkably, the upper-bound estimates suggested that 90% of these yield losses can be associated with the direct effects of SLCPs. This finding underscores the potential gains that could be achieved by addressing regional air pollution. By mitigating the direct climate change effects of LLGHGs through concerted efforts to reduce SLCP emissions, we could counter anticipated future yield losses and safeguard agricultural productivity in India.

Gupta et al. (2017) employed regression analysis using information from 208 districts to investigate the influence of temperature and aerosol pollution, on wheat yields in India from 1981 to 2009. Their results showed that an increase of 1°C in the daily average maximum and minimum temperatures corresponds to a decrease in yields by ∼2–4% each. They combined the estimated impacts of climate change on productivity along with aerosol pollution. The results revealed that a one-standard-deviation reduction in aerosol optical depth (AOD) is projected to enhance yields by ∼4.8%. These findings suggest that by mitigating regional air pollution and addressing global warming in the coming decades, it is possible to counter the losses in wheat yields.

3.3 Impact on human health

The amalgamation of climate change and air pollution has profound and multifaceted implications for human health (Kumar et al., 2019). The intricate interplay between climate change and air quality suggests that future strategies aimed at addressing these interconnected issues will gain advantages from increased coordination (Kinney, 2018). Young children, senior citizens, and pregnant women are particularly susceptible to the health risks associated with air pollution, as their respiratory and cardiovascular systems are more fragile and prone to damage (WHO, 2016, 2021; Sonwani et al., 2021a,b,c). Young children are particularly susceptible because they have faster breathing rates in comparison to adults (Sharma and Kumar, 2018, 2020), the breathing rate of children per unit of body weight is nearly double compared to that of adults (Harrison and Yin, 2000; Ginsberg et al., 2005; Heal et al., 2012) and their organ systems are in a phase of rapid growth and development. These effects have been discussed in detail in previous studies by Sharma and Kumar (2018, 2020).

People inhabiting in urban ecosystems are fragile to health impacts owing to high temperature and extreme pollution levels. Research has consistently shown that city temperatures tend to be higher than those in open rural areas, giving rise to the phenomenon known as the urban heat island (UHI) (Choudhury et al., 2023). In recent decades, many major global cities have undergone significant changes in land use and land cover, with far-reaching effects on their urban ecosystems. These changes have resulted in issues such as increased air pollution, traffic congestion, land degradation, and the emergence of urban heat islands (UHIs) (Yan et al., 2016; Liu et al., 2020). The connection between urban heat islands and climate change is a consequence of urbanization, industrialization and other human-induced factors. In developing countries such as India, where air quality deteriorates below acceptable levels (WHO, 2021), citizens from poor socioeconomic backgrounds are disproportionately affected due to health risks from air pollution (Kumar et al., 2015). The urban communities of our country are also subjected to extreme pollution levels and climate change impacts due to the UHI effect. According to a study conducted in Delhi (Singh et al., 2022) in the year 2000, the minimum temperature in Delhi was 23.2°C, and the maximum was 34.85°C. By 2010, these temperatures had increased to 26.31°C and 39.92°C, and in 2020, they further rose to 31.7°C and 44.74°C. This significant temperature rise over the years illustrates the UHI effect. Moreover, the normalized differential vegetation index (NDVI) has revealed a notable reduction in non-vegetated areas, decreasing from 82% to 62% due to rapid urbanization and changes in land use and land cover over the past two decades. These biophysical changes in the city's landscape clearly indicate that NDVI and land use/land cover modifications are the primary drivers behind the development of urban heat islands within the city. This worsens existing health inequalities and highlights the pressing demand for focused interventions to safeguard such vulnerable populations (Mathiarasan and Hüls, 2021). One crucial finding from epidemiological research is that babies transported in prams are highly vulnerable to air pollution. They breathe at lower heights, typically within 1 meter from the ground level and in close proximity to vehicle tailpipes emitting harmful pollutants (Sharma and Kumar, 2018, 2020) raises concerns about their long-term health and emphasizes the urgency of addressing air quality in urban environments.

To mitigate air pollution exposures, dedicated efforts are needed to quantify the obstacles and opportunities to effectively utilize scientific knowledge for managing air quality while accounting the diverse stakeholder's perspective (Muñoz-Pizza et al., 2022). Many of the researchers identified different COVID-19 lockdown phases as a proxy solution for air pollution mitigation, that may be implemented in future for such air pollution and climate benefits (Venter et al., 2020; Goel et al., 2021). For the effective implementation of such strategies requires effective atmospheric monitoring, emissions inventories, and compilation of health-related datasets particularly for developing countries. Further, to derive the necessary shift from an expert-based to a dialogue-based process will need dedicated attempts from multiple stakeholders including scientists, public policy makers, governors, and the citizens (Green et al., 2000). Deploying green infrastructure, promoting sustainable transport fuels with low life-cycle sustainability impacts, and improving public transportation can significantly reduce air pollution levels and improve air quality (Sharma, 2016; Abhijith et al., 2017; Abhijith and Kumar, 2019; Kumar et al., 2019). Moreover, community engagement to sensitize local citizens and policies targeted at reducing individual exposure to air pollution may play a pivotal role in safeguarding health (Kumar et al., 2015).

Tackling the health effects of climate change requires a universal perspective. A large share of responsibility of minimizing climate change lies with developed countries because they have historically emitted greenhouse gases. Still, its consequences are often felt most severely by poor people in developing countries (Kumar et al., 2015; Perera, 2018). As a result of this environmental injustice, it demonstrates the moral imperative for collective action to mitigate climate change, promote sustainable practices, and ensure that the burden of climate change does not fall disproportionately on the most vulnerable populations (Perera, 2017, 2018). In a nutshell, there should be a greater focus on environmental justice and equitable global responsibility to minimize air pollution exposure and address climate change impacts.

4 Climate change related extreme events in India

The threat of air pollution in India has risen, with its impact exacerbated by the influence of climate change. Under this section we list few among many extreme events reported in India that was triggered by climate change.

4.1 Flood

In December, 2015, Chennai experienced extreme one-day rainfall causing widespread flooding. The likely cause to be detected was aerosols counteracting with greenhouse gases (van Oldenborgh et al., 2016). Anthropogenic warming was also blamed for warm mean surface temperatures observed in 2015 according to CMIP5 simulations (Kam et al., 2016; Nanditha et al., 2020). Climate change was attributed as the cause for the total rainfall in northern India during June 2013 (Singh et al., 2014). Indian states situated in the flood-prone area of the Ganges-Brahmaputra-Meghna basin, encounters a series of unfavorable climate occurrences notably, annual floods. A study focused on the flood catastrophe that took place in the Ganga-Brahmaputra basin in 2020, impacting the regions of Bihar, West Bengal, and Assam during July, August, and September. They derived the flood extent using Google Earth Engine (GEE) and data from Sentinel-1A Synthetic Aperture Radar (SAR). The combined extent of floodwater inundation between July and September was calculated to be highest in Bihar (20,837 km^2) followed by West Bengal (17,307.1 km^2), and Assam (13,460.1 km^2) (Pandey et al., 2022). This event was attributed to global warming, sea level rise and climate change catalyzed glacier melting (Barman and Bhattacharjya, 2015; Janes et al., 2019; Loukas et al., 2021).

As a consequence of climate change induced warming, it was predicted that a 10–12% increase in precipitation and a sea level rise of approximately 50 cm could result in the submergence of numerous coastal cities in India, including Mumbai, Chennai, Goa, Kochi, Puducherry, Daman and Diu. This, in turn, would place an estimated 35–50 million Indians at risk of chronic flooding, potentially leading to loss of life (National Maritime Foundation, NMF).

4.2 Storms and cyclone

As a results of climate impact, several coastal cities experienced the high incidences of cyclonic events. Repeatedly, storms and cyclones have wrought havoc upon numerous villages in the coastal state of Odisha, which is frequently susceptible to tropical cyclones. Consequently, residents have been compelled to seek new habitation. A noticeable surge in the frequency of storms, and cyclones has been documented over the past few decades when compared to historical records (Subramanian et al., 2023). Sand and dust storms become very common in the North and West Indian region and have a variety of adverse impact on the environment. The principal consequences of these incidents encompass alterations in the atmospheric radiation balance, changes in regional precipitation patterns, and fluctuations in hurricane activity. Furthermore, dust storm events contribute to heightened concentrations of fine particulate matter in the atmosphere, which have been linked to adverse health effects such as premature mortality, cardiovascular issues, respiratory problems, lung cancer, and severe respiratory tract infections (Maji and Sonwani, 2022).

4.3 Forest fire

Globally it is recognized that ∼80% of forest fires are anthropogenic in nature (FAO, 2007). In India, ∼50% of the forest areas are classified as fire prone and > 95% of forest fires are of anthropogenic origin (Satendra and Kaushik, 2014). The occurrence, frequency, and intensity of forest fires is directly linked to changing climate conditions such as warmer temperature, precipitation deficits, increased number of dry days, and El Niño-Southern Oscillation (ENSO) events [National Oceanic and Atmospheric Administration (NOAA), 2021] that can lead to an increase in fire incidences (Nurdiati et al., 2022). It has also been recently investigated that, due to changing climate increasing the forest fire intensity, incidences and frequency increased by several fold in central Indian region, such increase was observed not only in the fire prone season, but also in the rest of the year (Jain et al., 2021).

4.4 Drought

Climate change also cause variability in precipitation, soil moisture, and surface water, as well as excessive groundwater extraction, resulting in draft conditions (Mukherjee et al., 2018). According to Roy et al. (2022), study in which the Drought Early Warning System (DEWS), a system that monitors drought conditions in real-time was used, estimated approximately 21.06% of India's landmass that experienced conditions similar to a drought. This represents a significant increase of 62% compared to the drought-affected area from the same period in the previous year, which was only 7.86%.

4.5 Heat waves and cold waves

Another study focusing on the projected heat waves in South Indian cities using CMIP predicted severe heat waves in the region (Nandi and Swain, 2022). Moreover, other research highlights extreme heat events (EHE) in Ahmedabad, it experienced severe heat waves in 2010 and 2016, recorded temperatures of 50°C

(122°F) (Patel et al., 2022). As far as cold waves in India concerned, the north, north-west, central, east India, north-east Peninsula, Jammu and Kashmir falls in the Core Cold Wave Zone (CCZ). The El-Niño event in India hampers the CW activities. Significant increasing trends in the heat waves days and noticeable reductions in the frequency of cold wave days, aligning with similar trends was observed in numerous regions worldwide (Pai and Nair, 2022).

5 India's urban transformation and climate change

Urban systems play a crucial role in achieving significant reductions in emissions and promoting the establishment of communities with the capacity to withstand and adapt to the effects of climate change. Cities need to consider various factors for both adaptation and mitigation, such as assessing climate addressing impacts and vulnerabilities by means of climate-related services in the planning and design of infrastructure and settlements. Strategies like compact urban planning, integrating jobs and housing, promoting public transportation and active modes of mobility like walking and cycling, as well as efficient construction, retrofitting, and energy-efficient use of buildings, contribute to these goals (Chen et al., 2008; Barton and Tsourou, 2013; Amado et al., 2016; Bibri et al., 2020; Verma et al., 2021).

Initially, concerns about climate change impacts in modern India primarily revolved around vulnerabilities to the many climate-related risks. This has led to initial efforts focusing on adaptation measures. The urban transformation in India is influenced by different aspects including population growth, changes in land use, and industrialization, that are multiplied by the impacts of climate change (Lele et al., 2018; Sonwani et al., 2021a,b,c). The diversity in climate risks across different urban areas in India is a reflection of local geographical and climatic conditions (Khosla and Bhardwaj, 2019). Hence, adaptation strategies need to be tailored to specific local contexts. Furthermore, environmental challenges like air pollution, dwindling green spaces, and water scarcity intersect with the effects of climate change (Ranjan and Narain, 2012; Dholakia and Garg, 2018; Gurjar et al., 2018).

India's role in these discussions is pivotal, given its projected substantial urban growth in the decades to come (United Nations Environment Programme, 2021). However, many Indian cities are still struggling with foundational issues like physical development, poverty, and environmental degradation. Integrating climate change considerations alongside these basic challenges poses a significant hurdle (Ürge-Vorsatz et al., 2018). The way these cities are constructed and expanded will shape consumption patterns, production practices, and subjected to climate-related risks over decades to come. Many cities lack adequate services, with inconsistent and inadequate access to essentials like water, sanitation, and drainage. A considerable proportion of urban dwellers live in inadequate living conditions, often termed "slums". The local environment's health, air, water quality and solid waste management, is severely compromised and ranks among the poorest at global level (Karak et al., 2012; Nixon et al., 2013; Singh et al., 2013). There are some India's strategies for dealing with multifaceted challenges like urbanization and climate change in terms of accessibility, inclusivity, and livelihoods and this emphasizes the urgency of decisions that can establish sustainable, low-carbon, and resilient modern societies (Creutzig et al., 2016; Ürge-Vorsatz et al., 2018).

The future path that urban India takes in responding to climate change depends on how effectively regional development and climate objectives are interconnected, combined, and given priority. The way urban areas are built over the next 10 years will significantly influence the consumption habits of the majority of Indians for the rest of the century. Implementing a well-coordinated urban climate strategy that spans different levels of government, taking into account the expansive nature urban layouts of India, and seizing the opportunity to establish sustainable infrastructures with reduced consumption, could play a pivotal role in shaping India's development trajectory. In recent years, urban areas have undergone significant societal and technological transformations that include a noticeable shift toward adopting low-carbon lifestyles (Roy et al., 2018). This shift was made possible by national-level policies and programs influenced by increasing research on modern day climate change. These policies encourage cities to embrace environmentally friendly practices. For example, initiatives like the National Mission on Sustainable Habitat, Smart Cities Mission, Solar City Program, and Green Urban Transport Mission together promote the implementation of rooftop solar panels, energy-efficient practices, public transportation, pedestrian pathways, separate lane for bikes, and building energy standards (Rajasekar et al., 2018; Taraporevala, 2018). Concurrently, efforts to enhance drain infrastructure under the Atal Mission for Rejuvenation and Urban Transformation are focused on improving urban climate resilience (Tewar et al., 2015). These localized and sector-specific measures for adaptation and mitigation, along with the associated literature, indicate an increasing recognition and a movement toward climate-focused strategies in urban India.

The initial steps taken for adaptation in urban India were led by two global networks: the Asian Cities Climate Change Resilience Network (ACCCRN) and ICLEI—Local Governments for Sustainability (Fisher, 2014; Khosla and Bhardwaj, 2019). The strategies employed for enhancing adaptation and resilience varied based on geographical locations, influenced by local vulnerabilities, risks, and existing infrastructure shortcomings (International Council of Local Environmental Initiatives-South Asia, 2014; UNDP, 2014; Yenneti et al., 2016; Dhyani et al., 2022).

Singh et al. (2021), studied the climate change approach adopted in some major Indian cities. Out of the 53 cities analyzed, each having a population exceeding 1 million, 38 cities have documented their efforts in either devising or executing strategies to mitigate the impacts of climate change. Additionally, 27 of these cities have outlined plans and, in some cases, already initiated actions geared toward adapting to climate challenges. The range of mitigation measures undertaken is extensive, spanning from the establishment of solar city initiatives in places like Chandigarh and Srinagar, to the development of blueprints for low carbon societies, as seen in Bhopal. Furthermore, more modest interventions have been integrated into smart city projects, encompassing elements like biogas installations and structures powered by solar energy. Among the subset of 27 cities prioritizing adaptation, a diverse array of approaches has been adopted. Some cities have placed an emphasis on systemic enhancements, manifesting in actions rooted in ecosystem preservation, such as the formulation of coastal zone management plans to oversee developmental activities along coastal regions, observed in cities like Mumbai and Chennai. Others have embraced wider nature-based solutions, such as the "Cities4forests" initiative in Kochi, which aims to safeguard, oversee, rehabilitate, and foster green spaces. Moreover, a distinct focus on managing risks is evident in certain cities, with initiatives including action plans to counter the effects of extreme heat, notable examples being Ahmedabad, Hyderabad, and Nagpur. Additionally, the widespread integration of cool roof technologies, notably in Ahmedabad, Indore, and Surat, forms another facet of this risk-focused approach.

6 Vulnerable communities

Climate change is expected to worsen existing disparities related to social factors like caste and gender (Saini et al., 2015), as well as economic aspects like class and geographic location (Ranjan and Narain, 2012). To call out on specific communities, climate change will particularly impact marginalized groups like the urban poor individuals, the elderly, children, and communities whose livelihoods are influenced by climatic patterns, like fisherfolk (Tran et al., 2013; Yenneti et al., 2016; Lundgren-Kownacki et al., 2018; Pandey and Kumar, 2018; Wilk et al., 2018). It is likely for India to experience more pronounced impacts of climate change, including disruptions to businesses, damage to infrastructure and homes, complications in mobility, and concerns for public health (World Bank, 2014). Among the most vulnerable are the urban poor, who experience insufficient access to essential resources and services. that could mitigate these risks. About 3.3 to 3.6 billion people reside in environments highly susceptible to climate change impacts. Vulnerability is closely intertwined between humans and ecosystems, with regions facing development constraints being particularly vulnerable to climatic hazards. From 2010 to 2020, regions characterized by high vulnerability saw a 15-fold increase in human fatalities resulting from floods, droughts, and storms when compared to areas with extremely low vulnerability (IPCC Report, 2022).

Resilience refers to the ability of economic, social, and environmental frameworks to withstand hazardous events, disturbances, or trends while maintaining their essential identity, function, and structure. Resilience also includes the capacity to evolve, learn, and adapt (IPCC, 2014). From a vulnerability perspective, incorporating community resources, risk can be defined as: Risk = (Hazard x Vulnerability)/Capacity. In this context, "capacity" refers to the amalgamation of assets and capabilities existing within a community, society, or organization that can reduce the levels of risk or mitigate the consequences of a disaster (Das et al., 2009). Numerous indices evaluate the vulnerability of various communities based on their socio-economic attributes. Indices like the Livelihood Vulnerability Index (LVI), LVI IPCC models, and Climate Vulnerability Index (CVI) are employed to assess climate change vulnerability in different livelihoods within urban communities, as seen in Guwahati city, Assam, India (Paul et al., 2019). Comparative analysis of these vulnerabilities indicated that farmers were the most vulnerable due to their increased sensitivity to health issues and financial setbacks amplified by a restricted ability to adapt. Conversely, doctors exhibited the least vulnerability due to their higher awareness levels and better adaptive capabilities. In addition to that, lowland and floodplain communities face significant vulnerability to climate change-induced extremes. Each year, river floods affect approximately 21 million people worldwide, a figure anticipated to rise to 54 million by 2030 as a result of the combined impacts of climate change and socio-economic expansion (Luo et al., 2015). The Ganga basin, due to its dense population and agricultural dependence, stands out as particularly susceptible to climate change (Pandey et al., 2022). The Brahmaputra basin's climate and geology have induced changes in river channels and led to bank erosion. The immense sediment load deposition in the Ganga-Brahmaputra delta, spanning 1.76 million km^2, contributes to one of the world's largest fluvial sediment depositions (Pandey et al., 2022). Annual floods deposit about 1,060 Mt of sediment load into the Ganga-Brahmaputra delta and Indian Ocean, constituting a significant alluvial sediment accumulation (Milliman and Farnsworth, 2013). Additionally, inhabitants of the delta regions contend with frequent flooding, sea-level rise, cyclone-induced storm surges, and climate change challenges (Woodruff et al., 2013). Indian states within the flood-prone region of the Ganges-Brahmaputra-Meghna basin experience adverse climate events that elevate vulnerability. Increasing temperatures, shifting rainfall patterns, and intensifying extreme weather events have collectively heightened the landscape risk (Kishore et al., 2022). More frequent and severe floods, driven by intense rainfall and prolonged monsoons, disrupt daily lives, harm infrastructure, and lead to loss of lives. These floods also pose significant challenges to agriculture and food security, as submerged crops result in failed harvests and livelihood losses.

7 Global climate change—Methodologies

Researchers around the globe utilize a variety of climate prediction models based on their climate change variable and subject. Bochenek and Ustrnul (2022) found that artificial neural networks (ANN) and deep learning (DL) were the most dominant algorithms in their analysis, with decision tree methods such as random forests (RF), extreme gradient boosting (XGB), and support vector machines (SVM) also being frequently used. These methods appear to be applicable to both Numerical Weather Prediction (NWP) and climate analysis. Their study also reported that majority of climate change studies are conducted in China, the USA, Australia, India, and Germany.

A 2D Convolutional Neural Network (CNN) has been suggested as a tool for approximating regional precipitation and discharge extremes based on synoptic-scale predictions from general circulation models (GCM) (Knighton et al., 2019). This approach not only allows for the identification of the most reliable fields in estimating extreme precipitation but also facilitates the recognition of important regional and seasonal variations. Machine learning techniques can also enhance the prediction of future intensity-duration-frequency curves, crucial for extreme precipitation and flooding events (Hu and Ayyub, 2019), or assist in estimating trends and seasonal components of rainfall (Ghaderpour et al., 2021).

Projections of emission and greenhouse gas concentration have been made up to 2300 for each Representative Concentration Pathway (RCP) scenario in the Coupled Model Intercomparison Project Phase 5 (CMIP5) and extended to 2500 by Meinshausen et al. (2011). Similar long-term projections are available up to 2500 for the Shared Socioeconomic Pathways (SSPs) in CMIP6 (Meinshausen et al., 2020). However, no comprehensive climate model results beyond 2300 are currently available. Many studies focusing on time horizons beyond 2100 have relied on Earth System models of reduced complexity or intermediate complexity (Palmer et al., 2020). Lyon et al. (2022) derived preliminary climate projections from the HadCM3 atmosphere-ocean coupled climate model and the TRIFFID dynamic land surface model which highlight the necessity of quantifying the effects of climate change beyond 2100. For instance, global mean temperature continues to raise after 2100 under most emission scenarios, except for the low-emission RCP2.6 scenario. Under the moderate-high RCP6.0 emissions scenario, global mean warming reaches 2.2°C above present-day levels by 2100 and further increases to 3.6°C in 2200 and 4.6°C in 2500.

Choudhury et al. (2023) employed a cellular automata-artificial neural network (CA-ANN) model to forecast the potential scenario of urban heat islands (UHIs) in 2032, indicating an anticipated intensification of land surface temperatures, particularly in rapidly urbanizing regions. Das et al. (2022) utilized a process-based dynamic vegetation modeling (MAPSS-CENTURY: MC) approach to project changes in vegetation life forms under projected climate conditions.

8 Climate change mitigations status and strategies for India

Enabling urban transitions that bring about positive outcomes for promoting mitigation, adaptation, human welfare, the provision of ecosystem services, and decreasing vulnerability within low-income communities necessitates comprehensive, enduring planning that incorporates both physical and natural elements as well as social infrastructure. The following mitigation measures are recommended for developing Asian countries:

i **Green and blue infrastructure:** Natural and blue infrastructure aids in capturing and storing carbon, and when combined with traditional gray infrastructure, it can decrease energy consumption and minimize risks associated with extreme events like heatwaves, flooding, heavy rainfall, and droughts. Furthermore, it provides supplementary advantages by enhancing health, quality of life, and means of living (UNEP, 2021; IPCC, 2023).

ii **Climate-smart approaches:** Approaches such as climate-resilient agriculture, disaster risk reduction that relies on ecosystems, and the investment in urban blue-green infrastructure effectively tackle adaptation, mitigation, and align with the Sustainable Development Goals all at once (Jha et al., 2013; UNDRR, 2021). These options open avenues for climate-resilient development pathways across India.

iii **Incorporating climate factors:** Decision-making processes at all levels of governance must incorporate climate risks, vulnerabilities, and adaptation strategies. This necessitates a deepened comprehension of climate impacts across sectors and time-space scales, along with enhancements to planning strategies and resource allocation (IPCC, 2023).

iv **Enhancing forecasting and decision making:** Appropriate prediction of extreme events, improved readiness to risk, and prioritization of individual and collective decision-making are imperative for effective climate action (UNFCCC, 2008; IPCC, 2023).

v **Transforming climate risks into opportunities:** Asian nations can transform climate change risks into opportunities by advancing the quality and sustainability of energy. This includes promoting investments in renewable energy sources, safe-gaurding gas reserves, advancement in water conservation techniques, choosing green infrastructure technologies, and fostering collaborations among various stakeholders (IPCC, 2023).

vi **Transitioning from fossil fuels:** In light of the current global scenario, a shift from fossil fuel-dependent economies to renewable resources and nature-based solutions is crucial for a sustainable future (UNDRR, 2021).

vii **Addressing deforestation and REDD+:** The ongoing process of deforestation and the deterioration of forests disrupts their crucial contribution to the worldwide carbon cycle. While REDD+ (Reducing Emissions from Deforestation and Forest Degradation) governance has an important part in mitigating climate change (Jenkins and Schaap, 2018), it requires a holistic approach that navigates through complex institutional landscapes and power dynamics to achieve desired outcomes. However, considering the magnitude of the climate issue and the requisite measures required in other greenhouse gas-emitting sectors, the role of REDD+ has limitations. Implementing REDD+ needs a comprehensive and robust approach (IPCC, 2023).

In conclusion, fostering urban transitions that are beneficial for multiple aspects of sustainability requires holistic planning, integration of various infrastructure types, and a deep understanding of climate impacts and adaptation strategies. The diverse options presented hold promise for addressing climate-related challenges and steering Asian nations toward resilient and sustainable development.

8.1 Nature based solutions as a potential mitigation strategy

The effects of climate change on both nature and people are initially felt within urban settings due to the microcosmic nature of cities and the fact that nearly 50% of world population inhabits urban areas (Metz et al., 2007). The ramifications of climate change on ecosystem functioning and human wellbeing are profound. The escalating frequency of heatwaves, droughts, and flooding further exacerbates socio-economic vulnerabilities. Challenges stemming from urban expansion, such as habitat loss, soil sealing, and increased built-up areas, compound the strain on ecosystem functionality, the delivery of ecosystem services, and human welfare across cities worldwide (Benedict and McMahon, 2006).

Nature-based solutions (NbS) emerge as a promising approach to counter these challenges. NbS capitalize on the inherent benefits of nature to tackle the effects of urbanization and climate change. They encompass interventions that incorporate nature into urban spaces to enhance resilience and wellbeing. One critical avenue of NbS is Urban Green Infrastructure (UGI), which aligns with the principles of NbS. UGI entails the strategic incorporation of green spaces into urban planning across various scales, and it underscores the role of nature in providing a multitude of services to urban populations. This concept stems from urban planning and highlights the pivotal role of green spaces in enhancing ecosystem services. UGI aims to strategically integrate green spaces into urban fabric, recognizing their significance in mitigating adverse climatic effects.

A notable facet of UGI and NbS pertains to the management of urban temperatures. By thoughtfully deploying urban green spaces, cities can significantly alter their microclimates. Urban parks, for instance, have been shown to mitigate temperatures during daytime hours by $\sim 1^{\circ}$C. Notably, larger parks with substantial tree cover exhibit a more pronounced cooling effect (Bowler et al., 2010). Additionally, the nature of surface materials influences the cooling impact. Water bodies, for example, exhibit lower surface temperatures than plantation areas, that are cooler compared to streets and rooftops (Leuzinger et al., 2010). This highlights the potential of water bodies for enhancing cooling effects and suggests concentrating such features in city centers to maximize their impact. Furthermore, the configuration of the urban environment has a critical role to play in the efficacy of temperature regulation efforts. Building structures and layout impact the degree of cooling achieved through green and blue infrastructure. Dense urban areas tend to benefit more from vegetation-based cooling, particularly when considering prevailing wind patterns and times of the day (Lehmann et al., 2014). Individual urban trees also contribute to temperature mitigation by reducing the Urban Heat Island (UHI) effect. The effectiveness of trees in this regard depends on factors like leaf arrangement and canopy shape. Innovative NbS, including green roofs and green walls, further influence urban energy dynamics and thermal moderation. Green walls, for instance, exhibit potential in reducing wall temperatures and mitigating street canyon temperatures, thereby furthering climate adaptation objectives (Cameron et al., 2014).

The choice and supervision of urban plantation amid evolving climate conditions are pivotal for sustained NbS effectiveness. As climate conditions evolve, plant species must be chosen with adaptability in mind. Optimal tree selection involves considerations of cooling efficiency, maintenance requirements, and additional ecosystem services like habitat creation and aesthetic value (Rahman et al., 2015). Design adjustments are necessary to accommodate changing rainfall patterns and increased water demand during droughts. This becomes specifically essential in high-density areas where space is at a premium. Maintaining healthy vegetation cover is essential for preserving ecosystem function. Green roofs, for instance, lower air temperatures by about 1°C and require consistent upkeep to ensure their efficacy (Speak, 2013). Neglecting maintenance compromises the cooling potential of these systems. The albedo effect, influenced by vegetation cover, impacts surface temperatures and underlines the importance of sustained green cover. Vegetation's role in altering building energy balances is another vital aspect. Simulation models highlight that urban greening can significantly reduce energy consumption and lower building temperatures, presenting an alternative to traditional sun-blocking methods (Yang et al., 2017). In urban hydrology, NbS demonstrate their effectiveness by mitigating local flooding and minimizing economic losses during moderate or frequent storm events. However, it's crucial to recognize that these solutions are not very effective in dealing with extensive and devastating occurrences like river floods and intense cloud bursts (Fletcher et al., 2015).

8.2 Indian cities and nature-based solutions

The Blue-Green Master plan of Delhi is a significant initiative aimed at enhancing the city's sustainability and resilience against climate change. This plan focuses on developing a multifunctional blue-green infrastructure that integrates both water and vegetation elements. By combining these elements, the plan seeks to address environmental challenges such as pollution, water scarcity, and inadequate green spaces. It emphasizes the interdependence of water bodies and land, creating a symbiotic relationship that offers various environmental and social benefits. The plan covers strategies for improving water management, green spaces, transportation, energy efficiency, and more, all integrated into a holistic approach for sustainable urban development (https://dda.org.in/pdf/july13/Final%20MPD%202041%20-%20e%20Gazette_%20English.pdf.).

Rajkot, a city in Gujarat, has developed a comprehensive Climate Change and Environment Action Plan to combat the impact of rising temperatures and climate change. This plan is a collaborative effort between the Climate Change Department, Government of Gujarat, and the Gujarat Ecological Education and Research Foundation. The plan focuses on reducing energy consumption, water conservation, air quality monitoring, waste management, and greenhouse gas reduction. It aims to create a more sustainable and climate-resilient city through a range of strategies, including renewable energy promotion, water conservation, waste reduction, and improved air quality monitoring (http://www.vasudha-foundation.org/wp-content/uploads/Full-Action-Plan-Rajkot.pdf.). In the case of Bangalore, often referred to as 'Greater Bangalore,' the exponential growth of industries and infrastructure has led to the depletion of green spaces and water bodies, contributing to elevated pollution levels and soaring temperatures. The implementation of NbS have the potential to impart a crucial role in alleviating these challenges. By prioritizing the expansion and preservation of green infrastructure such as parks, urban forests, and gardens, the city can effectively counteract the urban heat island effect and enhance the overall quality of the air (Nimish et al., 2022). This approach not only minimizes the environmental impact of urban expansion but also contributes to the city's long-term resilience against climate change.

Conversely, Nagpur is confronting distinct issues, including water scarcity, flash floods, and air pollution, exacerbated by the ongoing urban expansion. Here, too, NbS offer a promising path toward environmental equilibrium. Innovative strategies like curbside plantation, vertical gardens on buildings, and green roofs mitigate air pollution as well as aid in minimizing the urban heat island effect and enhancing stormwater management during heavy rainfall (Dhyani et al., 2021). Community engagement remains critical for the success of these solutions, with local participation ensuring their sustainability and effectiveness (Govindarajulu, 2014). Preservation of existing green spaces and the restoration of degraded ecosystems are equally important, as they contribute to enhancing biodiversity, maintaining ecological balance, and fostering a more resilient urban environment.

The adoption of sustainable advancements further strengthens the impact of NbS on climate change mitigation. In Bangalore, leveraging technological advancements in construction practices to create green buildings can significantly lower energy consumption while providing a healthier indoor environment (Smith, 2015). Similarly, in Nagpur, the integration of smart city technologies can optimize the allocation of resources for green infrastructure, enhancing the effectiveness of NbS (Jain et al., 2021). The difficulties created by climate change in Bangalore and Nagpur necessitate tailored nature-based solutions that consider the unique characteristics of each city. By embracing green infrastructure expansion, sustainable construction practices, and community engagement, both cities can address their respective environmental issues while paving the way for a more sustainable and resilient future. These endeavors also serve as valuable lessons for other urban areas grappling with similar challenges.

In summation, NbS offer a compelling pathway toward crafting livable, sustainable cities resilient to climate change impacts. The spectrum of vegetation-driven solutions caters to diverse adaptation needs. Strategic planning, informed by modeling and collaboration, is imperative to harness the full potential of NbS. These solutions mitigate the adverse impacts of climate change and represent a paradigm shift toward harmonious coexistence between urban spaces and the natural world.

8.3 Currents gaps and challenges in climate change mitigation for India

Indian cities face significant challenges in leveraging institutional capacities and incentives to harness systemic benefits, acknowledge climate-related synergies and trade-offs (Revi, 2008; Boyd and Ghosh, 2013; de Oliveira et al., 2013; Sethi and Mohapatra, 2013; Chu, 2015; Revi et al., 2016). After carefully reviewing several papers and reports the following gaps and challenges in climate-change mitigations have been identified:

- The basic environmental challenges faced due to climate change are temperature, altered rainfall patterns, hailstorms, cold waves, etc. that impact human health, livelihood, agriculture and economy.
- The widespread challenges arising from climate change encompass environmental, economic, socio-economic, socio-environmental, natural capital, agricultural vulnerability, water resources, and health issues (Gupta et al., 2020).
- In India, there's a notable absence of a comprehensive understanding of the interaction between climate concerns and developmental objectives at various levels of policy and governance. Short-term, discrete actions undertaken without an assessment of cumulative impacts often succumb to influences of vested interests.
- There exists a gap in adapting holistic strategy that integrates climate change considerations into urbanization planning at any governmental level. Central government initiatives like the Transit Oriented Development Policy, Green Urban Mobility Scheme, Unified Metropolitan Transport Authorities, and notably the Smart Cities Mission aim to achieve integrated urban governance. Urban climate action in cities is influenced by the involvement of higher government levels, which cities often depend on for central schemes and policy direction.
- India's unique socio-economic conditions, diverse geography, and varying climates pose challenges to implementing a uniform policy across the entire nation (Srivastava, 2021).
- The complexity of addressing social and environmental outcomes within REDD+ implementation, reporting, and accountability hampers progress, despite advancements in technology aiding in quantifying forest and carbon changes. Nonetheless, there's still room for improvement in measuring, reporting, and verifying both carbon and non-carbon outcomes. While various global initiatives aim to combat deforestation and forest degradation, they introduce complexities and opportunities for synergies with REDD+.
- Climate Resilient Development (CRD) faces substantial challenges such as fragmented and reactive governance, insufficient evidence for prioritizing actions and sequencing them, as well as financial deficits.
- Modeled trajectories aligned with Nationally Determined Contributions (NDCs) pre-COP26, until 2030, with no post-2030, exhibit higher emissions leading to a global warming of 2.8 [2.1–3.4] °C by 2100. Although many nations declare their aspirations to achieve net zero greenhouse gas (GHG) or net zero carbon dioxide (CO2) emissions by the mid-century, there exists a gap in the scope and specificity of pledges differ, with limited existing policies to fulfill them.
- Numerous obstacles are present in precise forecasting, but they can be overcome through the adoption of advanced technologies, including *in situ* observation, remote sensing, innovative sensor technologies, citizen science, artificial intelligence, and machine learning tools. Enhanced forecasting capabilities, regional partnerships, improved risk awareness, and leveraging technology contribute to overcoming these challenges.

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9 Conclusion

In conclusion, the vulnerability of developing nations in the area of climate change has become an undeniable reality, contrasting starkly with the more developed countries. This susceptibility stems from the intricate interplay of fragile ecosystems, precarious economic structures, and widespread poverty within these developing countries, as elucidated by various scholars (Panda, 2009). The transformations in land use resulting from rapid urbanization, altered river courses, shifting cultivation practices, erosion, and desertification, as outlined by experts (Chakraborty, 2009; Sreenivasulu and Bhaskar, 2010) profoundly shifts ecosystems. India, being a rapidly developing nation, has witnessed an alarming warming trend over the decades, leading to unprecedented weather extremes and heightened demand for cooling in the sweltering summers due to both climate change and population growth. It's crucial to underscore that marginalized urban communities, including the impoverished, elderly, children, and those dependent on climatic conditions like fisher folk, will be subjected to impacts of climate change. With larger share of global population dwelling in urban areas (Metz et al., 2007), the path that urban India takes in responding to these challenges holds substantial sway over consumption habits and overall sustainability. In this context, the adoption of nature-based solutions (NbS) emerges as a promising strategy, leveraging nature's innate capacities to counterbalance the impacts of urbanization and climate change. By integrating natural elements into urban landscapes, NbS not only bolster resilience but also promote well-being, offering a ray of hope amidst the encroaching climate crisis.

10 Future directions for climate change studies in India

The future work on climate change in India is a pressing and multifaceted challenge that requires a comprehensive approach to address its far-reaching impacts. India is a geographically diverse country, and future climate research should focus on region-specific impacts. Understanding how climate change affects different parts of India, considering variations in temperature, precipitation, and extreme events, is crucial for developing tailored adaptation strategies. Research should delve into the effects of climate change on agriculture, which remains a lifeline for millions. It's essential to develop climate-resilient farming practices, crop varieties, and water management systems to ensure food security in the face of changing climate patterns. With increasing water stress, studies on sustainable water resource management, including efficient irrigation techniques and groundwater replenishment strategies, are essential. Additionally, India's extensive coastline demands research that prioritizes the development of strategies to mitigate the impact of sea-level rise, including building resilient infrastructure and protecting vulnerable coastal communities. Future research should focus on urban planning, infrastructure development, and efficient energy use to enhance the resilience of cities. Leveraging data, technology, and remote sensing can aid in monitoring climate change and predicting its impacts accurately. Lastly, ensuring that climate policies are aligned with India's development goals and are their effective implementation is a crucial aspect of future work.

Author contributions

SH: Formal analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. EH: Formal analysis, Methodology, Writing – original draft. PS: Conceptualization, Investigation, Methodology, Resources, Validation, Visualization, Writing – review & editing. AS: Formal analysis, Investigation, Writing – original draft. PT: Data curation, Investigation, Writing – original draft. SS: Conceptualization, Formal analysis, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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