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Ecosystem services linked to nature-based solutions for resilient and sustainable cities in India

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Rampant urbanization and undervaluing of the natural ecosystem have detrimental impacts on urban spaces – increased flooding risk, increased air and water pollution, water stress, resource inefficiency, loss of biodiversity, and increased risk of ill health. Climate change further exacerbates the adverse impacts of urbanization. Despite the importance of the natural ecosystem, the blue and green spaces of the cities in India have drastically decreased. The present study highlights the degrading natural ecosystem, the negative impacts, and the need for resilience in Indian cities. Eco-centric approaches like nature-based solutions (NBS) are closely related to sustainability and resilience, offering a more efficient and cost-effective approach to urban development than traditional approaches. The paper explores the concept of NBS, focusing on ecosystem services as a 'living' and 'adaptable' tool to make cities resilient and sustainable with many regional implementations. It also focuses on the role of NBS in achieving the United Nations' Sustainable Development Goals (SDGs). The paper critically analyses the five notable NBS projects from different countries (USA, Canada, The Netherlands, China, and Australia) and further addresses the viabilities for NBS intervention in Indian cities. It is observed that the successful adaptation of NBS in urban development necessitates eco-centric policies, collaborative research, adaptive management practices, community engagement, and a strong emphasis on a multi-benefit approach. A proactive focus on ecosystem services is strongly recommended for Indian cities, which includes raising an understanding of the value of nature, introducing NBS at the planning stage, and encouraging investment in ecosystem-based approaches.

KEYWORDS

urbanization, ecosystem services, nature-based solutions, climate change, sustainable development goals, resilient cities

1 Introduction

Cities worldwide are grappling with resilience challenges arising from the complex interplay of climate risks, urbanization, biodiversity loss, diminishing ecosystem services, poverty, and increasing socioeconomic disparities (World Meteorological Organization (WMO), 2022; United Nations Environment Programme (UNEP), 2023). The impact of climate change is projected to lead to more frequent and severe natural hazards and climate-related extremes like floods, droughts, and heat waves. Moreover, urbanization can increase the vulnerability of urban communities and infrastructure to these hazards due to rapidly declining natural land-use land-cover (LULC), i.e., blue (waterbodies) and green (vegetation) spaces (Ghofrani et al., 2017). The combined impacts of rampant urbanization and climate change have become evident at the global scale– nearly 2 billion people lacked access to safe drinking water till 2021, and over 90 billion USD of global economic losses from various natural disasters in the first half of 2021 alone (United Nations, 2022; United Nations Environment Programme (UNEP), 2023). With the existing trends of rampant urbanization and climate change impacts, urban resilience challenges are anticipated to intensify (World Bank, 2021).

Disaster risk reduction and climate resilience used to focus mainly on grey infrastructure, which may not always be the most cost-effective, resilient, and sustainable option. Grey Infrastructure refers to the engineered assets and built structures like embankments, dams, stormwater drains, and wastewater treatment plants created to manage environmental and hydrological attributes. In recent decades, the significance of nature-based solutions (NBS) has been increasingly acknowledged for urban resilience. NBS is an umbrella concept covering a range of ecosystem-related approaches to address social, economic and environmental challenges while benefiting human well-being and biodiversity (Cohen-Shacham et al., 2016). In other words, the NBS interventions harness the natural elements and processes of healthy ecosystems to effectively address some of the most significant challenges of the present time, like climate change, water security, and natural disasters (Bozovic et al., 2017; Ghofrani et al., 2017; Dorst et al., 2019; Hamel and Tan, 2022). The benefits attained through NBS interventions are commonly referred to as ecosystem services. Numerous international agreements and initiatives, like the Sendai Framework for Disaster Risk Reduction, the Sustainable Development Goals (SDGs) and the Paris Climate Agreement, promote nature-based approaches and align with environmental and risk management goals to address climate risk and environmental degradation and promote investment in disaster risk reduction (Reguero et al., 2020; World Bank, 2021). In the present study, the concept of NBS, including its ecosystem services, has been discussed with various successful case studies across the globe, and the possibilities of adaptation for the development of resilient cities in India have been explored.

2 Declining natural LULC compromising resilience and sustainability of cities in India

2.1 A brief description of land use transition in a few major Indian cities

This section discusses the trend of urbanization and declining natural LULC of a few major Indian cities and their suburbs, emphasizing the need for resilient cities in India. The increase in built-up area in the National Capital Territory (NCT) of Delhi was 162.7 sq. km to 531.2 sq. km from 1993 to 2018 (Bondwal and Bisht, 2019). The same study found that the forest cover in the NCT of Delhi decreased from 155.8 sq. km to 130 sq. km between 1993 and 2018. Land-use transitions are not only limited to the cities but also greatly affect suburban regions (Naikoo et al., 2020). Mumbai city experienced a significant decline in natural land use and land cover (LULC) from 1977 to 2017, with a 60 percent reduction in vegetation and a 65 percent reduction in waterbodies (Udas-Mankikar and Driver, 2021). Another study reported that the built-up area of Mumbai rose from 28 to 57% of the city's total area from 1991 to 2018, and it is projected to reach 66% by 2030 (Naikoo et al., 2023). Similarly, the Chennai Metropolitan Area (CMA) witnessed an increase in built-up areas from 18 to 48% and a decrease in vegetation from 57 to 26% between 1988 and 2017 (Mathan and Krishnaveni, 2020). Developments have taken over 90 per cent of the wetlands of Chennai city (Ahmad and Hassan, 2024). Bengaluru city experienced a significant decrease in the green cover of the city, more than 50% from 2003 to 2021, while the built-up area almost doubled during the same period (Keerthi-Naidu and Chundeli, 2023).

2.2 Need for resilient and sustainable cities in India

The consequences of the rampant land use transition in urban and suburban landscapes in India can be seen as increased urban pressures, i.e., flood risk, water stress, water pollution, urban heat island (UHI) and air pollution. The natural drainage systems in most cities are facing threats from encroachment, inadequate maintenance, poor solid waste management, and lack of adequately designed stormwater drainage infrastructure. For example, Chennai city suffered the most disastrous flood of the century in 2015, causing more than 400 human casualties, nearly 2 million severely affected and about USD 80 billion of estimated loss (Vojinovic, 2015). On the contrary, four years later, in June 2019, the city was unexpectedly hit by 'Day Zero,' and all of its major reservoirs dried up. The city has a minimum of 108 Litre per capita per day (LPCD) of water supply, much less than the WHO minimum criteria of 150 LPCD (Rajaveni et al., 2016). The study confirms the presence of UHI in Chennai with an intensity of 4.5°C in winter and 2.5°C in summer (Rajan and Amirtham, 2021).

The annual economic impact of urban flooding in India is disastrous, ranging from USD 1.1 billion to USD 5 billion (Sharief and Vangipuram, 2022). The highest UHI intensity recorded internationally is as high as 12°C, while the observed maximum UHI intensity in India is 8–9°C. UHI can deteriorate the urban environment in multiple ways – increase in energy and water consumption, higher emissions of pollutants into the atmosphere resulting in the greenhouse effect, heat-related health discomfort, and degradation of water quality in streams, rivers, and other water bodies (Jain and Sarkar, 2017; Veena et al., 2020; Vujovic et al., 2021). Every city and its suburbs face the abovementioned urban pressures with varying intensities depending on the type of city (like coastal city, riverine city, or mountainous city). The lack of effective streamlining, regulation, and monitoring of urbanization processes is a key factor contributing to significant environmental degradation. Taking account of climate change, environmental risks, and socio-economic vulnerability, there is an urgent need for a paradigm shift in urban developments in India and the adaptation of nature-based solutions for the development of resilient cities. NBS strategies optimize the climate-related risks with other objectives to achieve multiple benefits regarding ecological, socio-economic and overall urban well-being (Roumeau et al., 2015; Vojinovic, 2015). The concept of nature-based solutions and the associated ecosystem services have been discussed in detail in the next section.

3 Nature-based solutions (NBS): an approach for resilient cities

3.1 Overview of the NBS concept

The World Bank introduced the NBS concept in the late 2000s to address increasing climate-related risks, promoting ecosystem-based approaches (World Bank, 2008). The International Union for Conservation of Nature (IUCN) has been taking the lead in conserving the ecosystem and promoting nature-based solutions (NBS) globally by formulating core principles and frameworks for mainstreaming NBS. Figure 1 highlights the timeline of major milestones in developing the NBS concept. In recent years, the definition and scope of nature-based solutions have become vast and diverse. The diversity of concepts and definitions has led to challenges in achieving conceptual clarity, making the term more subjective (European Commission, 2021; Cohen-Shacham et al., 2016; Albert et al., 2017; Dhyani et al., 2020). Table 1 enlists the two most widely accepted definitions of NBS. Fundamentally, NBS is a novel approach that primarily focuses on using ecosystems to address climatic, environmental, and socio-economic challenges (Balian et al., 2014; Cohen-Shacham et al., 2016; Depietri and McPhearson, 2017; Dorst et al., 2019). Figure 2 depicts a distinct range of ecosystem and natural capital-based approaches under the NBS concept (Dhyani et al., 2020). Ecosystems demonstrate a remarkable ability to mitigate the adverse effects of climate-related risks and safeguard communities (Diaz et al., 2015; Lo, 2016).

NBS encompass the use of natural processes and ecosystems to create infrastructure, provide services, and develop comprehensive strategies to enhance urban resilience. World Bank identifies some NBS typologies like urban forests, urban farming, green corridors, river and stream renaturation, river floodplains, bioretention areas, and wetlands (World Bank, 2021). These approaches typically transcend traditional boundaries and necessitate collaborative efforts across various sectors. Nature-based solutions offer diverse advantages for cities, such as mitigating disaster risks, strengthening climate resilience, ensuring food-water security, promoting biodiversity restoration, and overall community well-being. Numerous terminologies under nature-based concepts have been developed in different parts of the world, such as ‘green infrastructure’ (GI), ‘blue-green infrastructure’ (BGI), ‘natural infrastructure’ (NI), ‘low impact development’ (LID), and ‘ecosystem-based adaptation’ (EBA). The terms NBS, GI, BGI, LID, EBA and sustainable measures are interchangeably used in the present study.

3.2 Integration of NBS measures across a range of spatial scales

There is a hierarchy of approaches for implementing the NBS umbrella concept as strategic planning, i.e., ‘protection and sustainable management of existing natural infrastructure’, ‘restoration and rehabilitation of degraded one’ and then ‘creation of new NBS’ (Cohen-Shacham et al., 2019). It is essential to consider this hierarchy when identifying and prioritizing nature-based solutions opportunities at a strategic level, such as when evaluating investment options for a city. These three approaches must be applied to plan and prepare NBS projects across various spatial scales. Generally, NBS is implemented at three spatial scales – neighborhood scale, city scale and river basin scale. At each scale, various NBS families can be implemented. For instance, floodplain restoration projects that restore natural hydraulic and hydrological connectivity can effectively mitigate flood hazards at the river basin level, while green roofs and bioswales can be strategically designed for implementation at the neighborhood scale (Liberalesso et al., 2020; Puchol-Salort et al., 2021). Measures (like urban forests, constructed wetlands and rivers and streams renaturation) at the city scale aim to enhance urban land use planning and strengthen the city’s disaster risk management. Figure 3 depicts the schematic section of NBS at the neighborhood, city, and river basin scales.

3.3 Methodology

The study presents a constructive exploration of NBS and its associated ecosystem services, featuring a range of successful regional implementations, as shown in Table 2. The reviewed literature included technical reports, project summaries, academic publications, government publications, conference proceedings, and resources from web search engines and academic databases (‘Web of Sciences’ and ‘Scopus’) for regional and city-scale NBS interventions. Search keywords include various NBS measures – green corridors, green roofs, urban forests and parks, urban agriculture, bioswales, rain gardens, retention ponds, permeable pavements, natural wetlands, constructed wetlands, stream renaturation and floodplain restoration.

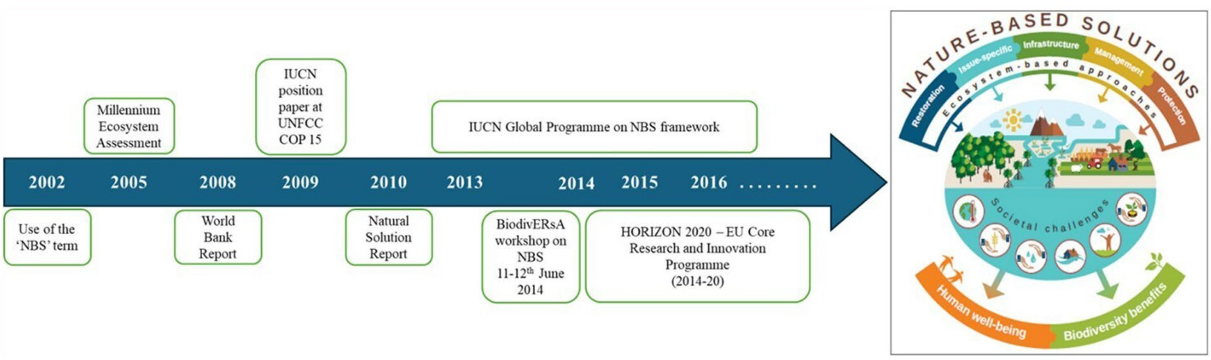

FIGURE 1
Milestones in the development of NBS concept [adapted from Cohen-Shacham et al. (2016)].

TABLE 1 Two most widely accepted definitions of NBS.

Organization name	Definition	References
European Commission (EC)	"Inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience."	European Commission (2021)
International Union for Conservation of Nature (IUCN)	"Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits."	Cohen-Shacham et al. (2016)

Further, five long-term city-scale NBS projects were selected to gain a worldwide perspective and foster the development of resilient cities in India (as mentioned in section 3.5). The number of NBS measures adopted simultaneously and the wide range of ecosystem services were used as selection criteria for the city-scale NBS exemplars examined in the study. It is worth mentioning that while no formal surveys were conducted with city officials, the findings still offer valuable insights for future discussions and research in the context of the development of resilient cities in India.

3.4 Ecosystem services and SDGs linked to NBS

The natural ecosystem can deliver multiple environmental and socio-economic benefits, which are called ecosystem services. Figure 4 depicts the pertinent processes related to ecosystem services for urban resilience. A few major ecosystem services related to NBS are briefly discussed below, along with the role of NBS in achieving SDGs.

3.4.1 Stormwater management and flood risk mitigation

Cities worldwide face the challenges of stormwater management and flood risk management (pluvial, fluvial or coastal), depending on the rainfall patterns, urbanization-induced LULC transitions, location (riverine, coastal, mountainous), and population growth. Considering the rise in impervious surfaces and increased extreme weather events, NBS can be implemented in the cities to mitigate the risks due to floods and combined sewer overflow (CSO) events by promoting infiltration and evapotranspiration (U.S. Environmental Protection Agency (USEPA), 2010; Shakya and Ahiablame, 2021; Ahmad and Hassan, 2024). Reducing the volume of stormwater entering the sewer system during rain events can alleviate pressure on the sewer system. A study related to flood regulation in three Australian capital city regions, SEQ, Melbourne and Perth, emphasizes the importance of green open spaces (Victoria State Government (VSG), 2017; Schuch et al., 2017). Similarly, in a study from Taichung City in Taiwan, different NBS measures (infiltration ponds, infiltration swales, and rain barrels) were evaluated using the stormwater management model (SWMM), showing the reduced annual runoff by 43.5–54.5 percent (Lin et al., 2018).

3.4.2 Urban heat island (UHI) mitigation

In urban areas, buildings and paved surfaces change thermal properties and radiative behavior compared to natural surroundings, creating distinct environmental impacts. These surfaces absorb solar radiation, contributing to elevated surface and ambient temperatures in urban areas as compared to rural areas, creating what is known as an "urban heat island" effect (Arrau and Peña, 2011; Killingsworth et al., 2011). The urban heat island phenomenon can lead to health issues such as heat stroke and even death during heat waves (U.S. Environmental Protection Agency (USEPA), 2003). Due to this effect, cities across the globe are becoming warmer than surrounding suburban areas in the summer. Implementing measures like green roofs and trees can lower temperatures through evapotranspiration, helping to mitigate urban heat island effects and improve public health (Killingsworth et al., 2011; Pitman et al., 2015). For instance, a study assessing the benefits and costs of green roofs in Toronto has shown that widespread adoption of green roofs could reduce local ambient air temperatures by 0.5°C to 2°C (Banting et al., 2005).

3.4.3 Improved water quality and groundwater recharge

NBS practices, such as green infrastructure (GI) measures, have proven effective in enhancing the quality of stormwater runoff. GI measures work by slowing down and filtering the polluted runoff before it enters adjacent water bodies such as lakes and rivers (Liu et al., 2015; Brumley et al., 2018; Yu and Li, 2023). Additionally, NBS include a range of measures (shown in Table 2) to improve water quality and promote groundwater replenishment (Brumley et al., 2018; Natural Resource Defence Council (NRDC), 2022). For instance, the restoration project of Genetta Park and Genetta Stream in Montgomery, in the United States, has been creating positive impacts on the Genetta Stream by mitigating downstream floods, improving water quality, enhancing stream biodiversity, and promoting groundwater recharge.

3.4.4 Improved air quality

Nature-based measures (such as green roofs, rain gardens, green facades, and green roads) are vital in mitigating air pollution, reducing emissions, and extending the distance between pollution sources and receptors (Hewitt et al., 2020). Vegetation enhances air quality by filtering out airborne pollutants and toxic gases, such as particulate matter (PM_{10}) and ozone (O_3). Additionally, the adoption of green infrastructure practices under NBS strategies in buildings leads to reduced energy consumption, which in turn helps improve air quality

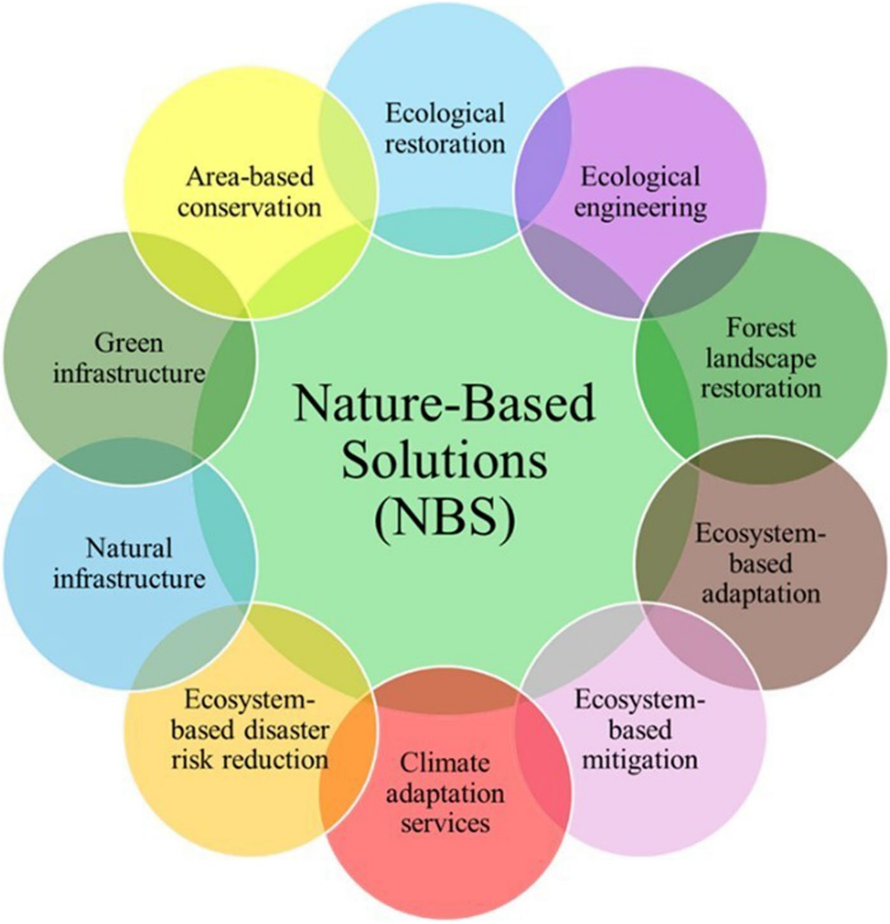

FIGURE 2
Ecosystem-related approaches under the present scope of NBS.

by lowering the emission of sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) (Yang et al., 2005; Wang et al., 2014). The Blue Green Wave is a one-hectare green roof, the largest in the entire Paris region in France, improving air quality with other ecosystem services like stormwater management and UHI mitigation (Brown and Mijic, 2019). Such initiatives have also been seen in Asian countries at different scales, like the Centenary Park in Bangkok, Thailand and 'pocket parks' in Kuala Lumpur, Malaysia (Holmes, 2019; Hamel and Tan, 2022).

3.4.5 Recreation and community well-being

Recent studies highlight the significance of GI measures under NBS strategies in urban areas for providing essential ecosystem services. GI measures use natural processes for infrastructure development and land use planning to promote economic and social development (Osei et al., 2022). Incorporating GI practices like urban parks, forests, green roofs, streams, ponds, swales, wetlands and community gardens into new developments and urban renewal projects to create new green spaces has been proven to enhance community liveability and offer opportunities for recreational activities, thereby contributing to improved public health and well-being (Wolch et al., 2014; Pamukcu-Albers et al., 2021).

3.4.6 Achieving SDG targets through NBS

The effective adaptation of NBS diminishes urban susceptibility to climate-related risks and contributes to attaining the United Nations' SDGs (Mahmoud et al., 2022; Kiribou et al., 2024). Acharya et al. (2020) investigated new methods to improve nature-based approaches to accomplish SDGs while focusing on transformative strategies and outlining responsibilities for communities, private sectors, and government organizations. Lombardía and Gómez-Villarino (2023) conducted a systematic review demonstrating how GI measures can facilitate SDGs in metropolitan regions and emphasized the need for increased support from policymakers and urban planners. Most SDGs are interconnected and mutually reinforce each other in various ways. An Australian study revealed that achieving 100% of the SDGs by 2030 is a significant challenge, but it is projected to achieve 70% (Allen et al., 2019). Table 3 summarizes the role of NBS in achieving all the SDGs and their varying relative importance (High >60%, moderate 30–60%, and low <30%), and each contribution is supported by a range of references. NBS directly contributes to SDG3, SDG6, SDG11, SDG13, and SDG15 by providing multiple cost-effective urban ecosystem services.

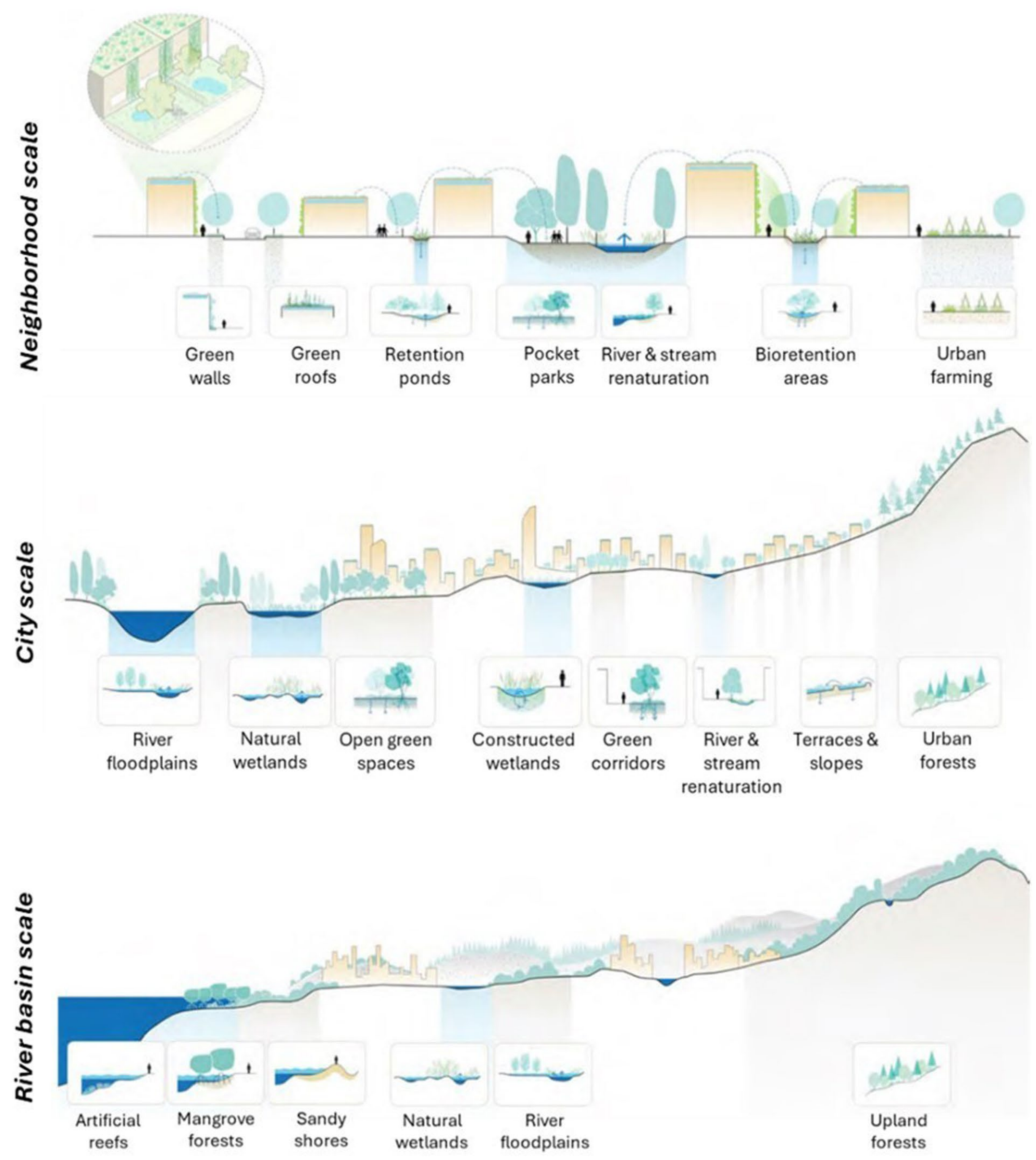

FIGURE 3
Schematic section of NBS at different scales [adapted from World Bank (2021)].

3.5 NBS in practice on the ground: key lessons learnt from the exemplars across the globe

In recent decades, there has been a growing trend toward using nature-based solutions for sustainable and resilient cities. Countries like the United States, the United Kingdom, the Netherlands, Germany, and many more have seen notable success in managing urban pressures through nature-based practices. The European countries have tremendously succeeded in developing the NBS strategies for urban resilience. In Asia, countries like China, Malaysia, Singapore, Japan and Thailand have also been working on the NBS implementation for various urban ecosystem services for a long time. As research into nature-based intervention expands, many such projects have been launched and completed successfully in cities worldwide. Therefore, five NBS projects from different countries (USA, Canada, The Netherlands, China, and Australia) have been selected to understand a worldwide perspective. All the

TABLE 2 NBS measures and some regional implementations and studies.

NBS measures	Ecosystem services	Few regional implementations	References
Green corridors	UHI mitigation, Pluvial flood mitigation, carbon sequestration, water & air quality, biodiversity, recreation and community well-being	• 'The Rail Corridor' -Singapore • 'Green Belt of Vitoria-Gasteiz'-Spain • Street trees, Portland, United States • Many implementations in Europe, the US, Canada, China, Australia	Norton et al. (2015), Lim and Lu (2016), Victoria State Government (VSG) (2017), O'Donnell et al. (2019), and World Bank (2021)
Green roofs	Pluvial flood mitigation, UHI mitigation, water & air quality, biodiversity, and community well-being	• 'Blue Green Wave'-the largest green roof in Paris (France) • 'ABC Programme'-Singapore • 'Eco-Roofs'- Portland, United States • Common examples – London (UK), Brussels (Germany), Seoul (South Korea), Victoria (Australia), Cairo (Egypt)	Mentens et al. (2006), Shafique et al. (2016), Lim and Lu (2016), Victoria State Government (VSG) (2017), Maryati and Humaira (2017), and Brown and Mijic (2019)
Urban forests and parks	Pluvial flood mitigation, UHI mitigation, carbon sequestration, water & air quality, resource efficiency, biodiversity, recreation and community well-being	• 'Centenary Park' – Bangkok (Thailand) • 'Pocket parks'- Copenhagen (Denmark) and Kuala Lumpur (Malaysia) • Urban forests in Toronto, Canada • High Line Park in New York (US)	Surma (2013), Norton et al. (2015), Holmes (2019), United States Department of Agriculture (USDA) Forest Service (2020), Udas-Mankikar and Driver (2021), Puchol-Salort et al. (2021), and Hamel and Tan (2022)
Urban agriculture	Food security, resource efficiency, Pluvial flood mitigation, carbon sequestration, UHI mitigation, and community well-being	• Urban Agriculture Practices in Lima (Peru). • Urban farming with 'Sponge City Program'in Chinese cities • Medium to large-scale practices in Jakarta (Indonesia) • Other examples- New York (US), Mexico City (Mexico); Bologna (Italy), Bangkok (Thailand)	World Bank (2013), Artmann and Sartison (2018), Sanyé-Mengual et al. (2020), Akter and Gupta (2022), and Zhu et al. (2023)
Engineered bioretention areas (bioswales, rain gardens, and retention ponds)	Pluvial and riverine flood mitigation, water quality and sediment management, carbon sequestration, biodiversity, UHI mitigation, recreation and community well-being	• 'Copenhagen Climate Change Adaptation Plan' in Copenhagen Metropolitan Area, Denmark • Many cities in the US like, Seattle, Lincoln, New York, Philadelphia • Bioswales of Riga city in Latvia • Sponge City Program (SCP) for Chinese cities	Sidek et al. (2013), Kato et al. (2017), O'Donnell et al. (2019), Lin et al. (2018), Wang et al. (2019), Hermawan et al. (2020), United States Department of Agriculture (USDA) Forest Service (2020), Natural Resource Defence Council (NRDC) (2022), and Kondratenko et al. (2024)
Green parking lots and Permeable pavements	Pluvial flood mitigation, UHI mitigation, water & air quality,	• 'Green Street Program' of Portland, US • Montgomery in Maryland, US • 'SCP-permeable pavements' in Wuhan, China • Taichung city of Taiwan • Many cities of US, UK, Australia, Indonesia	U.S. Environmental Protection Agency (USEPA) (2008), Montgomery County Planning Commission (MCPC) (2011), Li et al. (2017), O'Donnell et al. (2019), Puchol-Salort et al. (2021), and Natural Resource Defence Council (NRDC) (2022)
Natural wetlands and Constructed wetlands	Pluvial and riverine flood mitigation, water quality and sediment management, biodiversity, UHI mitigation, carbon sequestration, resource efficiency, recreation and community well-being	• Wetlands in Mississippi river basin, US • 'Qunli National Wetland' in Qunli, China • Natural wetlands in city of Columbia, Sri Lanka • Natural wetlands in Phnom Penh (Cambodia) • Constructed inland wetlands in Beijing (China), Bangkok (Thailand)	United States Army Corps of Engineers (USACE) (2012), Irvine et al. (2015), Holmes (2019), Agaton and Guila (2023), Shah et al. (2023), and Ganapathi et al. (2024)
Stream renaturation and floodplain restoration	Pluvial and riverine flood mitigation, water quality and sediment management, resource efficiency, carbon sequestration, UHI mitigation biodiversity, recreation and community well-being	• Odra River floodplain project (2007–20) in Wroclaw city (Poland) • Rio Bogota Environmental Flood Control Project (2011–21) in Bogota (Colombia) • Mississippi floodplain restoration (USA) • 'Room for the River' program in Nijmegen City (The Netherlands)	United States Army Corps of Engineers (USACE) (2012), Schindler et al. (2014), European Environmental Agency (EEA) (2017), European Environmental Agency (EEA) (2018), Steger et al. (2019), World Bank (2021), and Ahmad and Hassan (2021)

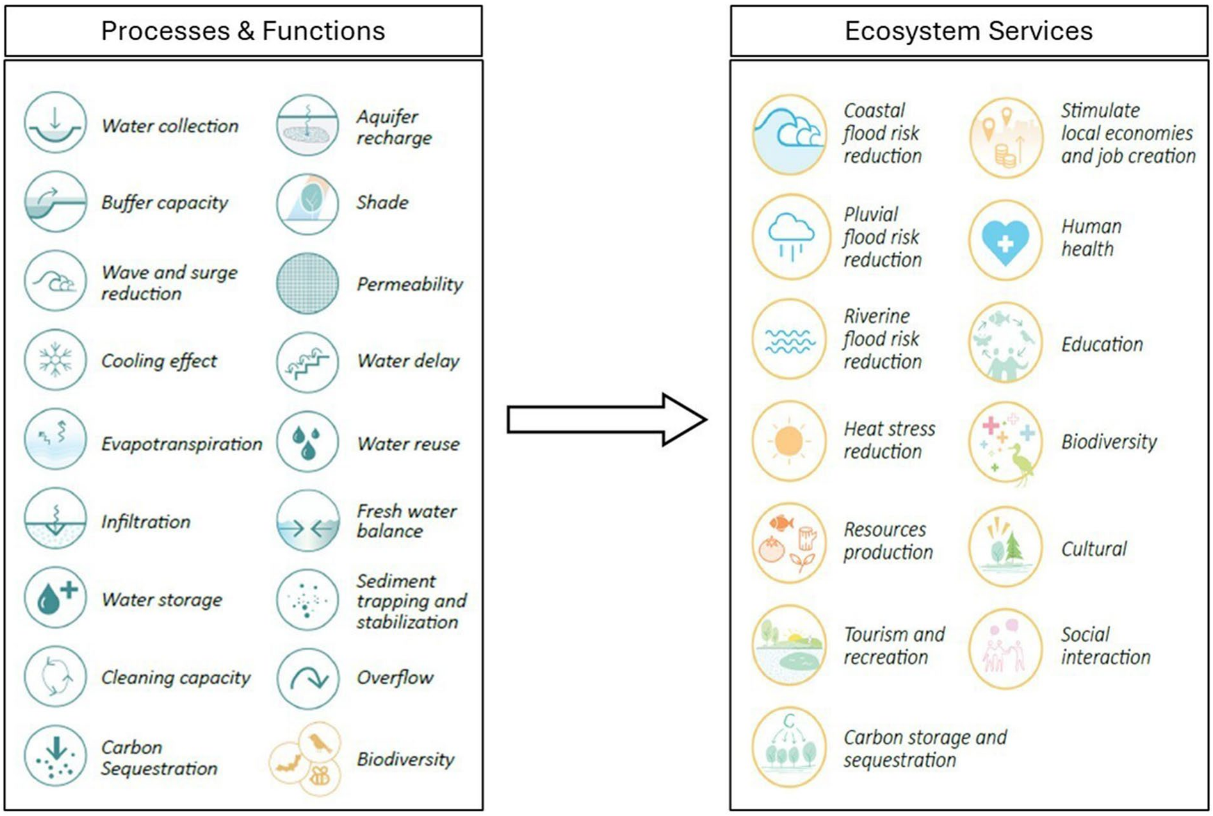

FIGURE 4
Relevant processes and ecosystem services of NBS concerning urban resilience.

selected projects have been critically analyzed, and their major objectives and the key lessons learnt have been presented in Table 4. The key learnings from these city-scale NBS projects include the effective combination of green and grey infrastructure to optimize urban water management and enhance urban resilience, implementing adaptive management practices, community engagement and awareness, and a strong emphasis on a multi-benefit approach.

4 Addressing the viabilities for NBS implementation in Indian cities

4.1 Challenges in NBS intervention in the cities of India

As the demand for resilient cities grows and NBS intervention plans are being developed, several challenges have emerged in implementing NBS in urban areas. These challenges span technical, social, and institutional factors. Indian cities face unique urban pressures due to their diverse socio-economic culture, demography, and climate. Despite the vital role of blue and green spaces for the environment and community well-being, these natural spaces are decreasing, and impermeable surfaces are rising in the cities. Analyzing the factors responsible for increasing urban pressures in Indian cities, some of the major challenges in NBS intervention that need to be addressed are as follows.

4.1.1 Degrading natural landscapes in cities and limited space

Rapid and unplanned urbanization has reduced the blue and green spaces (waterbodies and vegetation) in many Indian cities over time. The older cities (like Delhi, Mumbai, Chennai, Kolkata, and Bengaluru) have grappled with rampant urbanization and high population density. These factors create urban pressures like UHI and declined natural urban drainage, posing significant challenges for the existing combined sewer system. Designing and remodeling separate sewer systems with sustainable drainage measures or any NBS measures at the city scale in high-density areas will be intricate. This limitation of natural spaces hinders the integration of various nature and ecosystem-based measures such as urban parks, gardens, lakes, retention ponds, and wetlands within the city. Furthermore, implementing NBS at the building scales (like blue-green roofs, urban agriculture and rainwater harvesting measures) for other urban ecosystem services is also quite challenging due to unplanned settlements within and around the cities.

4.1.2 Climate and hydrology

Specific BGI measures can exhibit performance limitations due to varying climatic and hydrological behavior in different parts of the country. For instance, coastal cities with shallow groundwater levels will face challenges in implementing infiltration-based GI measures like bioswales and rain gardens. Cities with a minor rainy season and limited water resources may increase their water demand due to the

TABLE 3 Sustainable development goals (SDGs) through the NBS.

SDG title	NBS contributions to SDGs	Relevance order
No poverty (SDG1)	• Community gardens historically helped alleviate poverty in Europe and provided food for factory workers during the war and industrial revolution (Cabral et al., 2017). • It also helps developing nations in building resilience, where urban agriculture is essential due to unemployment and increasing food demand (De Bon et al., 2009; Douglas, 2018).	High
Zero hunger (SDG2)	• NBS can enhance crop production in urban regions to meet the food demand, promoting resilience (Cassman and Grassini, 2020). • Urban agriculture improves food security in developed and developing nations, ensuring access to food for vulnerable communities (Besthorn, 2013; Kahane et al., 2013; Clark and Nicholas, 2013).	High
Good health and well-being (SDG3)	• Green plants can remove major air pollutants like NO_2, improving urban air quality. • NBS can also enhance the water and soil quality of cities. • It could provide sustainable development with good health and overall well-being (Dora et al., 2015; Panagopoulos et al., 2016).	Moderate
Quality education (SDG4)	• NBS practices like urban agriculture not only impart knowledge to children and seniors but also equip low-income workers with new skills (Sterling et al., 2017) • Many studies elucidate the potential of GI to promote environmental education and social and professional growth, offering experiential learning opportunities for individuals of all ages (Cohen and Reynolds, 2015).	Low
Gender equality (SDG5)	• In developed countries, the practice of small-scale organic agriculture by urban women is undeniably growing with a primary motivation of factors such as lifestyle choice, self-dependent, and a strong sense of social commitment and education (Jarosz, 2011).	Low
Clean water and sanitation (SDG6)	• NBS practices like GI can potentially enhance water quality by removing pollutants like heavy metals. • Reinforcing urban drainage systems with GI measures can mitigate social and environmental risks (Dong et al., 2017).	Moderate
Affordable and clean energy (SDG7)	• GI measures like green roofs, green facades, and urban parks facilitate cities for low-energy consumption (Safikhani et al., 2014; Besir and Cuce, 2018).	Moderate
Decent work and economic growth (SDG8)	• NBS has the potential to create more urban jobs and increase property values in green regions of urban areas (Maes and Jacobs, 2017). Many studies have validated that GI measures, especially urban forests, to cater the socio-economic needs of the cities (Capotorti et al., 2015).	Moderate
Industry, innovation, and infrastructure (SDG9)	• Research indicates that by adopting green strategies, cities can achieve resilience. • Establishing a green infrastructure network could empower social, economic, and environmental systems to exhibit resistance, recoverability, and robustness – the key attributes of resilient socio-ecological systems (Grafton et al., 2019).	Moderate
Reduced inequalities (SDG10)	• Ecosystem-based practices like urban agriculture foster social cohesion and cooperation (Corcoran and Kettle, 2015). It helps in creating an inclusive and equal society with policies based on social justice.	Low
Sustainable cities and communities (SDG11)	• An integrated approach to GI measures with existing grey infrastructures promotes sustainable cities (Corbett and Mellouli, 2017). • GI measures provide multiple cost-effective ecosystem services, such as reduced flood risks, improved water and air quality, UHI mitigation, and overall well-being (Keeler et al., 2019).	High
Responsible consumption and production (SDG12)	• Local food production from urban agriculture can sustainably facilitate consumption and production cycles (Olsson et al., 2016; Pigford et al., 2018). • Vacant land in urban and suburban regions could be utilized for biofuel production to support energy demand sustainably (Niblick et al., 2013).	Moderate
Climate action (SDG13)	• There is growing evidence of NBS facilitating climate change adaptation by CO_2 sequestration and UHI mitigation (Wang and Zacharias, 2015; Wang et al., 2016). • Land-use transition with adequately integrated GI measures could enhance carbon sequestration from 5 to 30% (Roe et al., 2019); therefore, urban vegetation can reduce global emissions (Kulak et al., 2013; Macreadie et al., 2019).	High
Life below water (SDG14)	• Ecosystem-based approaches foster sustainability in coastal regions by enhancing ecosystem services, reducing flood risk, improving water storage, minimizing marine pollution, and promoting biodiversity in oceans (Keesstra et al., 2018b; Thacker et al., 2019). • Constructed wetlands and restoring the natural wetlands enable coastal areas to exhibit resilience.	Moderate

(Continued)

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TABLE 3 (Continued)

SDG title	NBS contributions to SDGs	Relevance order
Life on land (SDG15)	• NBS conserves and enhances soil productivity, and also facilitates biodiversity conservation (Keesstra et al., 2016; Keesstra et al., 2018a). • Urban GI measures provide a network for urban wildlife, pollinators and microorganisms while also impacting the socio-economic sector and human well-being (Hou et al., 2014; Hall et al., 2017; Akinsemolu, 2018). • These measures can greatly contribute to sustainability by providing an ecosystem for biodiversity.	High
Peace, justice and strong institutions (SDG16)	• Adequate integration of NBS in urban regions leads to a sustainable and resilient city, which can be reflected in the governance perspective. • It ultimately strengthens socio-economic and environmental institutions and promotes a peaceful, inclusive society (Wamsler et al., 2013; Maes et al., 2019)	Moderate
Partnerships for the goals (SDG17)	• Proper implementation of the NBS in urban spaces requires collaboration among decision-makers and other stakeholders (Murphy et al., 2019). • Public-private entities and citizens can collaborate to enhance the existing urban ecosystem and develop strategies for ecosystem-based adaptations (Fritz et al., 2019).	Moderate

water requirements of the crops, thereby limiting the use of green roofs, urban farming, and other vegetation-based infrastructures.

4.1.3 Limited NBS research and uncertainties

Due to the existing knowledge gaps and limited research on nature-based solutions in India, there are uncertainties regarding the hydrologic and ecologic performance of NBS. The lack of understanding and research regarding the adaptation of ecosystem-based approaches in India might result in initial resistance from urban planners and local authorities, who might overlook the potential ecosystem services linked to green infrastructure and other ecosystem-based strategies. Limited research with insufficient data also hinders NBS intervention on a city or river basin scale, creating uncertainty regarding the effectiveness of NBS, i.e., which approach would yield immediate versus sustained results.

4.1.4 Socio-economic constraints

Recent studies have provided more useful insights into the socio-economic constraints of non-traditional measures in urban development (Almaaitah et al., 2021; Mumtaz, 2021). Lack of community awareness and challenges in the economic valuation of the ecosystem services can create difficulties in justifying investments in nature-based approaches, especially compared to traditional methods. Apart from a social reluctance to support novel practices due to the lack of awareness, implementing NBS measures (like green roofs, urban agriculture, and rainwater harvesting) can be costly and challenging for retrofitting in dense urban agglomerations.

4.1.5 Lack of enforceable standards at the policymaking and planning level

The Government of India has taken significant steps to tackle urban transformation through the "Atal Mission for Rejuvenation and Urban Transformation" (AMRUT) program. The program focuses on enhancing urban infrastructure in 500 cities, emphasizing areas such as stormwater drainage, water supply, sewerage, green spaces, and public transport (Gupta, 2020). 'Smart City Mission' is also an initiative emphasizing sustainable solutions for urban development. Nevertheless, there remains a need for enforceable standards for incorporating NBS with proper specifications at the planning and policy-making stage. The government needs to create a statutory body by institutionalizing the NBS framework, which will ensure the implementation of the projects at the local level with specific standards.

4.2 Overcoming the challenges in NBS intervention in India from a global perspective

Various studies have been conducted worldwide to develop strategies to address the challenges (social, institutional and technical) associated with NBS interventions. Financial constraints are recognized as an institutional challenge. Studies highlight that social and institutional barriers tend to outweigh technical barriers (O'Donnell et al., 2017; Thorne et al., 2018; O'Donnell et al., 2021). Case studies of numerous cities emphasize the importance of a comprehensive approach to overcome these challenges. It is crucial to raise awareness, secure diverse funding sources, integrate green infrastructures into new developments,

TABLE 4 Some exemplary NBS projects in five major cities worldwide and key lessons learnt.

NBS projects	Metropolis	Population/Area (km^2)	Major objectives	Key lessons	References
NYC Green Infrastructure Plan (2010–2030)	New York (USA)	1,95,67,410 (34,490 km^2)	• To reduce CSO through sustainable stormwater management practices, target 1.5 billion gallons per year • To implement GI such as green roofs, right-of-way bioswales, green streets, and street trees for urban water management with additional UES	• Integration of Green and Grey Infrastructure to optimize water management and improve urban resilience • Adaptive management practices allowing flexibility based on performance and conditions • Community engagement and awareness • Focus on multi-benefit approach	Department of Environmental Protection (DEP) (2010), McPhearson et al. (2014), Culligan (2019), and Shakya and Ahiablame (2021)
Sponge City Program (2013-present)	Wuhan (China) – 30 pilot cities	6,31,486 (114 km^2)	• To absorb 60–85% of annual precipitation by 2030 and manage pluvial floods • To meet the sponge city standards by 2030 • To improve water quality, ensure water security and mitigate UHI through the NBS intervention	• Utilizes NBS measures for effective FRM and improved water quality • GI supportive policies and regulations • Developed localized strategies and technical standards tailored to specific urban contexts • Community and stakeholder engagement in the planning and implementation	Fenner (2020), Chen et al. (2021), Udas-Mankikar and Driver (2021), Qi et al. (2021), and Peng and Reilly (2021)
Green Infrastructure Vision 2050 (2020–2050)	Amsterdam (The Netherlands)	11,82,000 (220 km^2)	• To develop green routes for a 10-min walk from your front door to a park • To transform pavements into green spaces, wherever feasible, for the natural environment • To increase public green areas like parks and urban forests social well-being, climate adaptation, health, and biodiversity	• Emphasizing GI-integrated holistic urban planning • Developing climate resilience in extreme weather conditions • Long-term economic benefits through cost reduction in stormwater management, energy consumption, and healthcare • Community awareness and sensitization toward NBS	Paulin et al. (2019), Carbon Neutral Cities (2020), Department of Planning and Sustainability (DPS) (2020), and Kottari (2021)
Rain City Strategy (2020–2050)	Vancouver (Canada)	1,06,00,000 (8,494 km^2)	• To transform Vancouver into a resilient city and enhance its livability through GI measures • To improve the City's water quality • Increase greeneries, UHI mitigation and rainwater harvesting • To invest in education and capacity building to increase ecosystem-based adaptations	• Focus on integrating GI across public and private properties for effective rainwater management • Maximizes the investment in NBS through a multi-benefit approach • Community engagement and education • Establishes clear performance standards, adaptive management and regular monitoring	Rain City Strategy (2019) and Udas-Mankikar and Driver (2021)
30-Year Plan for Greater Adelaide (2010–2040)	Greater Adelaide (Australia)	15,15,491 (10,873 km^2)	• To transform the city into a sustainable and resilient one against climate risks by 2040 • To maintain and improve livability through NBS • Promoting public transport, cycling and walking • To protect, restore and enhance the natural environment	• Focus on creating compact urban forms to preserve the natural landscapes and reduce urban agglomeration • Promoting the sustainable transportation • Emphasizing the integration of GI in urban planning • Participation of residents in planning helps to foster a sense of responsibility for the natural landscape	Living Adelaide (2017), Australian Bureau of Statistics (ABS) (2021), and Greater Adelaide Regional Plan (GARP) (2021)

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and increase overall funding for nature-based projects within cities (Iojă et al., 2018; O'Donnell et al., 2021). Drawing insights from multiple studies and frameworks addressing the challenges in NBS intervention in urban areas worldwide (O'Donnell et al., 2017; Melville-Shreeve et al., 2018; Amaral et al., 2021; Toxopeus and Polzin, 2021; Suleiman, 2021; Castelo et al., 2023), six key steps have been identified for formulating strategies to tackle the implementation challenges in India. These steps include – (a) amending legislation and developing the policies to establish guidelines for nature-based measures with specific standards, (b) highlighting and promoting the numerous co-benefits of NBS-integrated multifunctional spaces, (c) encouraging collaborative efforts from research and planning to execution (d) increasing awareness through education, community events, and activities, (e) securing sustainable funding by involving the private sector (f) promoting the advanced scientific research on retrofitting NBS measures in existing urban settings and creating new ones.

Researchers also presented the strategies at various stakeholder levels to conceptualize and streamline the framework for NBS intervention (Qiao et al., 2018; Landscape Institute and the Construction Industry Council (LI and CIC), 2019; O'Donnell et al., 2020). Similarly, the stakeholders can be selected to institutionalize the NBS in the urban landscapes in India. It will define a framework at each stakeholder level to overcome these challenges. These stakeholders include the central government, state governments, academia, practitioners, and individuals. The central government should acknowledge the benefits of NBS and promote its nationwide adoption by revising legislation, establishing technical standards, empowering states to create regional policies, and facilitating collaborative research. State governments should promote the benefits of blue-green infrastructures at the local level, invest in outreach programs to educate communities, develop policies for adoption and maintenance, and secure funding through private-sector collaboration.

Taking on financial constraints and investing in blue-green infrastructure necessitates a proactive approach, including conducting a thorough cost–benefit analysis. For example, developing a robust framework to assess the socioeconomic impact of a flood event can provide valuable insights for comparing the economic benefits of blue-green infrastructure to the local community and the investors. The role of academia and practitioners in the development of strategies to overcome technical and financial issues is inevitable. The academia should enhance scientific understanding of the nature-based approaches through rigorous collaborative research with international organizations to fill the knowledge gaps and provide evidence regarding the hydrological and ecological performance of NBS. Researchers can also advocate for policy changes that support the implementation of NBS by publishing the research outcomes. With the collaboration of academia, practitioners need to develop low-maintenance blue-green infrastructure measures, assess their suitability for regional environments, create open-source toolkits to assess and monetize the ecosystem services and raise public awareness about the co-benefits. Assessing the ecosystem services and further monetizing them will also draw the attention of the private sector to invest in nature-based projects for urban sustainability and resilience.

Citizen engagement can facilitate cities through the problem-based model to identify the local challenges, connect people with nature and increase the sense of ownership of NBS-intervened places to overcome the challenges. Communities working with natural processes and systems can facilitate better adaptability of nature-based projects (Brown and Mijic, 2019). Individuals should take part in local stewardship efforts for nature conservation, actively engage in the ongoing NBS projects, provide valuable support, and strive for sustainable development. Encouraging behavior change among fellow citizens is also important, as it raises awareness about the multifaceted NBS-integrated urban spaces.

5 Conclusion

The study emphasizes the declining natural LULC in Indian urban landscapes and the urgent need for sustainable and resilient cities. NBS has gained recognition for enhancing urban resilience, addressing environmental and climate challenges, and promoting community well-being and biodiversity. NBS offers various ecosystem services (such as flood risk mitigation, improved water and air quality, urban heat island mitigation, and resource efficiency). The present study provides a detailed analysis of the ecosystem services linked to NBS, focusing on how these ecosystem-based strategies can facilitate SDGs.

To explore the potential integration of NBS in India, five exemplary NBS projects from different countries have been analyzed – NYC Green Infrastructure Plan (USA), Sponge City Program (China), Green Infrastructure Vision (The Netherlands), Rain City Strategy (Canada), 30-Year Plan for Greater Adelaide (Australia). Learning from global initiatives can be a significant step toward developing ecosystem-based strategies to understand and address the resilience challenges against the increasing urban pressures in Indian cities. The valuable insights drawn from these city-scale projects highlight the integration of green and traditional infrastructure for improved urban water management and enhanced urban resilience. Additionally, these projects emphasize the significance of employing adaptive management techniques, fostering community involvement and awareness, and prioritizing a multi-faceted approach to achieve multiple benefits.

Various challenges (technical, social, and institutional) related to NBS intervention in Indian cities have also been discussed. Limited research exists to compare the effectiveness of NBS with traditional grey infrastructure alternatives. Comprehensive research on nature-based solutions, particularly implementation and suitability consideration frameworks, is very much needed in India. It will be instrumental in quantifying the environmental benefits, facilitating urban water management, and developing climate change adaptation and mitigation strategies. It will also support the formulation of ecosystem-based policies and encourage investment from the private sector. Moreover, introducing NBS during the planning and policymaking phase, setting clear standards for NBS deliverables, encouraging stakeholders' participation and collaborative efforts, and ensuring practical implementation can maximize ecosystem services, enhancing sustainable development, economic growth, and urban resilience.

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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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