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ORIGINAL RESEARCH ARTICLE

Nature-based solutions for climate change mitigation: A perspective on challenges, potential and limitations

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ABSTRACT

This opinion article delves into the critical role of nature-based solutions (NbS) for climate change mitigation. Despite their recognized potential, the multifaceted challenges of NbS remain complex and under-explored. Both potential and limitations are discussed, including economic, social, and political considerations. The importance of an interdisciplinary approach and adaptation to diverse socioeconomic and cultural contexts to ensure equitable implementation of NbS is highlighted. This brief but critical perspective seeks to enrich the academic view and provide actionable insights for urban planners and policymakers. Finally, it proposes directions for future studies for researchers in the fields of sustainable urban development and climate change mitigation.

Keywords: resilience; sustainability; climate change; anthropocene; urbanization

Opinion

The intensification of extreme weather events underscores the urgent need to prevent and mitigate their impacts on urban ecosystems and human well-being[1–3]. Within this context, Nature-based Solutions (NbS) emerge as a promising approach[4–6]. However, despite their recognized potential, the multifaceted challenges of NbS for climate change mitigation remain complex and under-explored. Existing studies vary in methodologies and scopes, revealing that while some emphasize immediate risks, others focus on long-term projections, demanding a careful view to avoid overgeneralization.

NbS, comprising components such as green roofs, permeable pavements, and urban forests, serves as a dynamic approach to confronting these issues[7–9]. Current literature addresses the intricate interplay between urban development, environmental stressors, and the performance of NbS. Many of the studies emphasize environmental benefits without a comprehensive exploration of limitations and challenges, suggesting the need for more critical perspectives that integrate technical, social, and economic aspects.

This article endeavors to contribute to bridging this gap by offering a critical perspective on the limitations and challenges of NbS, thereby enriching the understanding of its role in fostering sustainable urban development. By delving into the mechanisms underpinning resilience in the face of climate-induced challenges, we seek to advance the discourse surrounding the role of NbS in climate change mitigation. By

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doing so, we aspire to not only enrich the academic view but also provide insights for urban planners and policymakers.

Overall, NbS is rooted in the concept of harnessing the inherent capacity of natural ecosystems to address environmental challenges. Drawing on ecological principles, NbS involves the strategic use of natural processes to enhance resilience, mitigate climate change impacts, and promote sustainable development. The theoretical underpinnings of NbS emphasize the importance of working with nature to achieve multiple benefits, encompassing ecological, social, and economic dimensions[10–12].

Numerous elements within NbS play indispensable roles in the multifaceted challenge of climate change mitigation. Green roofs, for instance, represent an innovative approach by introducing vegetation atop buildings, offering benefits such as enhanced insulation, reduced urban heat island effects, and efficient carbon sequestration[13,14]. Quaranta et al.[15] provide a comprehensive model assessing green roof performances across Europe, emphasizing their crucial role in urban climate change mitigation. This study underscores green roofs' potential for cooling urban landscapes, thereby reducing the urban heat island effect and enhancing urban resilience to climate change. Additionally, Sayad et al.[16] further validate the effectiveness of green roofs in mitigating urban heat islands, as explored in Annaba City. Their findings highlight significant reductions in surface temperatures, contributing to a more sustainable urban microclimate. Moreover, Zheng and Chen[17] demonstrate the impact of green roofs in Shanghai, where their implementation not only facilitated energy savings in buildings but also significantly reduced air pollution.

Permeable pavements, another crucial component, go beyond traditional pavement functionality. They facilitate the infiltration of rainwater into the ground, reducing surface runoff and preventing issues such as flooding and soil erosion[18,19]. Zhu et al.[20] highlighted the role of permeable pavements in reducing carbon emissions during the use phase of pavements, emphasizing their contribution to climate change mitigation. Additionally, Mamajonova et al.[21] discussed how permeable pavements, along with other green spaces, can significantly contribute to global climate change mitigation efforts. Moreover, Ashofteh and Dougaheh[22] demonstrated the effectiveness of permeable pavements under climate change conditions, showing a significant reduction in flood volume in a region of Korea. These studies collectively show that the permeable nature of these pavements aids in groundwater recharge and contributes to sustainable water resource management. By minimizing storm water runoff, permeable pavements play a vital role in climate-resilient urban design.

Urban forests, with their dense tree canopies and green spaces, stand as essential contributors to climate change mitigation[23]. Beyond their aesthetic appeal, these urban ecosystems play a pivotal role in carbon sequestration through photosynthesis, helping offset greenhouse gas emissions. Chen et al.[24] evaluated carbon storage based on climate change scenarios at the city level, emphasizing the significant role of urban forests in carbon sequestration. Furthermore, Locke et al.[25] explored the relationship between urban tree canopy and air temperature reduction, illustrating the cooling effects of urban forests, which are vital in reducing ambient temperatures and alleviating the urban heat island effect. Sousa-Silva and Zanocco[26] also highlighted the importance of urban green spaces, including forests, as a heat adaptation strategy, further underscoring their role in fostering biodiversity and enhancing urban resilience against extreme weather events. These studies collectively demonstrate the multifaceted benefits of urban forests for climate change mitigation and urban environmental management.

In the realm of transportation, sustainable systems are paramount to mitigating climate change. Examples include well-designed public transportation networks, cycling infrastructure, and the promotion of electric vehicles[27,28]. Recent studies have emphasized the impact of public transit systems on reducing individual carbon footprints and traffic congestion, thereby curbing emissions. Zhou et al.[29] explored the economic analysis of an online DC-driven transportation system, emphasizing its contribution to carbon reduction in response to climate change. Moreover, Ibekwe et al.[30] discussed the transition towards sustainable and secure energy futures, considering the increasing importance of climate change mitigation and the imperative to develop sustainable transportation systems. Additionally, Umoh et al.[31] reviewed the incorporation of energy efficiency in urban planning, highlighting the reimagining of transportation systems as a crucial factor.

Furthermore, the widespread adoption of energy-efficient buildings contributes significantly to reducing overall greenhouse gas emissions, aligning with sustainable urban development goals[32]. A study by Umoh et al.[31] highlights green architecture and energy efficiency, emphasizing innovative design and construction techniques that contribute to the overall reduction of greenhouse gas emissions. Another study by Umoh et al.[33] in the realm of urban planning emphasizes the importance of incorporating energy efficiency into building regulations to reduce carbon emissions. These studies underscore the critical role of energy-efficient buildings in achieving sustainability goals by reducing energy consumption and associated emissions.

Table 1 provides a comparative overview of the reviewed studies, highlighting their objectives, key findings, NbS addressed, and applications.

Table 1. NbS for climate change mitigation: objectives, key findings and applications.

Study	Objective	Key Findings	NbS	Application
Quaranta et al.[15]	Develop a model to estimate the performance of green roofs across Europe	Importance of green roofs in mitigating climate change in cities	Green Roofs	Climate regulation, biodiversity
Sayad et al.[16]	Investigate urban heat island phenomenon in Annaba city	Effectiveness of green roofs in mitigating climate change and urban heat island phenomenon	Green Roofs	Urban heat island reduction
Zheng and Chen[17]	Model the effect of green roofs on energy savings and air pollution reduction	Green roofs contribute significantly to energy savings and air pollution reduction	Green Roofs	Energy savings, air pollution reduction
Zhu et al.[20]	Review carbon emission quantification and reduction in pavement use phase	Importance of pavement choice in reducing carbon emissions	Pavements	Carbon emission reduction
Mamajonova et al.[21]	Explore the role of green spaces in urban planning	Green spaces significantly contribute to urban sustainability and quality of life	Green Spaces	Quality of life improvement, sustainability
Ashofteh and Dougaheh[22]	Evaluate low-impact urban development systems under climate change conditions	Optimal combinations of low-impact urban development systems for climate change mitigation	Urban Systems	Climate change mitigation
Chen et al.[24]	Project LULC dynamics and ecosystem services in urban agglomerations	Significant impact of urban forests and other NbS on ecological dynamics and ecosystem services	Urban Forests	Carbon sequestration, cooling effects
Locke et al.[25]	Assess the relationship between urban tree canopy and air temperature	Significant cooling effects of urban trees, especially in varied climatic conditions	Urban Trees	Air temperature reduction, air quality improvement
Sousa-Silva and Zanocco[26]	Assess public attitudes towards urban green spaces as a heat adaptation strategy	Recognition of the importance of urban green spaces in heat adaptation and life quality	Green Spaces	Heat adaptation strategy, life quality improvement
Zhou et al.[29]	Economic analysis of an Online DC-Driven Transportation System	Potential for carbon reduction and contribution to climate response	Sustainable Transport	Carbon reduction, sustainable development

Table 1. (*Continued*).

Study	Objective	Key Findings	NbS	Application
Ibekwe et al.[30]	Comprehensive review on energy security and geopolitical dynamics	Importance of sustainable transportation systems for energy security and mitigation	Sustainable Transport	Energy security, climate change mitigation
Umoh et al.[31]	Review policies and best practices for incorporating energy efficiency in urban planning	Importance of policies to promote energy efficiency in buildings and urban planning	Urban Planning	Energy efficiency, carbon emission reduction
Umoh et al.[33]	Review design and construction techniques for green architecture	Innovative techniques for green and energy-efficient building construction	Green Architecture	Energy efficiency, sustainability

A comparative analysis of these studies on NbS and climate change mitigation reveals significant insights into the diverse applications, benefits, and challenges in different contexts. The studies by Quaranta et al.[15], Sayad et al.[16], and Zheng and Chen[17] focus on green roofs, demonstrating their effectiveness in climate regulation, biodiversity promotion, and reducing urban heat islands, particularly in densely populated urban areas like Shanghai and Annaba.

In contrast, studies on urban green spaces by Mamajonova et al.[21], Chen et al.[24], and Sousa-Silva and Zanocco[26] highlight the broader ecological and societal benefits of NbS. They stress the importance of urban forests and green spaces in enhancing quality of life, fostering biodiversity, and offering cost-effective solutions for urban sustainability.

The emphasis on sustainable transportation in studies by Zhou et al.[29] and Ibekwe et al.[30] reflects a growing recognition of the need for low-carbon transport options in response to global climate challenges. These studies underline the potential for sustainable transportation systems to contribute to energy security and climate change mitigation.

Lastly, the reviews by Umoh et al.[31] on green architecture and urban planning underline the critical role of energy-efficient designs and policies in reducing greenhouse gas emissions. These studies advocate for integrated approaches to urban development that align architectural innovation with sustainable practices.

Overall, the comparative analysis underscores the multi-faceted nature of NbS and their vital role in addressing environmental, social, and economic challenges in the face of global climate change. Each study contributes unique perspectives and findings, enriching the understanding of how NbS can be effectively implemented in various urban contexts.

The integration of these diverse infrastructural elements aligns seamlessly with the principles of NbS, fostering a more sustainable, resilient, and climate-responsive urban environment. These examples illustrate how combining green roofs, permeable pavements, urban forests, sustainable transportation, and energy-efficient buildings can create a synergistic effect, forming a comprehensive approach to climate change mitigation in urban areas. This holistic strategy not only addresses environmental concerns but also enhances the overall livability and adaptability of urban spaces in the face of climate challenges.

In the context of urban environments, the enhancement of resilience through NbS involves a nuanced interplay of diverse and interconnected mechanisms. A prime example of this is the role of vegetation in acting as a carbon sink[34]. Here, green spaces with lush vegetation facilitate the absorption of atmospheric carbon dioxide through the process of photosynthesis, effectively sequestering carbon. This not only aids in mitigating the overall carbon footprint of urban areas but also contributes to the global effort to counteract climate change.

Furthermore, the mitigation of the urban heat island effect is a crucial mechanism facilitated by NbS in urban settings[35]. The expansive use of impervious surfaces, such as concrete and asphalt, in urban landscapes tends to absorb and retain heat, leading to elevated temperatures compared to surrounding rural areas. Green infrastructure, particularly through the strategic planting of trees and vegetation, provides shade and facilitates evaporative cooling, reducing ambient temperatures. By mitigating the urban heat island effect, cities can alleviate heat-related stress on residents, improve overall air quality, and enhance the comfort and livability of urban spaces.

Reducing energy consumption is another significant mechanism through which urban green infrastructure enhances resilience[36]. Trees strategically positioned around buildings can provide natural shading, reducing the need for air conditioning during hot seasons. Additionally, green roofs and walls offer insulation, regulating indoor temperatures and minimizing the demand for artificial heating or cooling. This not only results in energy savings but also contributes to the overall efficiency and sustainability of urban energy systems.

The creation and maintenance of biodiverse green spaces represent yet another mechanism supporting urban resilience[37]. Beyond their aesthetic appeal, these green spaces harbor a diverse range of plant and animal species, fostering ecosystems within the urban fabric. This biodiversity promotes ecological balance, enhances soil health, and supports pollinators crucial for urban agriculture. The adaptive capacity of these biodiverse ecosystems becomes particularly evident in the face of environmental stressors, as diverse ecosystems are often more resilient to disturbances and better equipped to recover from adverse events.

Moreover, urban green infrastructure serves as a natural buffer against extreme weather events, such as floods and storms[38]. For instance, vegetated areas and permeable surfaces absorb and slow down rainwater runoff, reducing the risk of flooding during heavy precipitation. Trees and green spaces act as physical barriers, minimizing wind and stormwater damage to buildings and infrastructure. By functioning as a natural buffer, green infrastructure significantly contributes to reducing vulnerability, enhancing overall urban resilience, and protecting against the impacts of climate-induced extreme events.

In essence, the multifaceted contributions of NbS, encompassing carbon sequestration, heat island mitigation, energy conservation, biodiversity support, and resilience against extreme weather events, collectively form a robust and comprehensive suite of mechanisms. These mechanisms not only address immediate environmental concerns but also contribute to creating adaptable, sustainable, and livable urban environments in the face of ongoing climate challenges.

Cities worldwide are increasingly adopting NbS to address the challenges posed by climate change. Notable instances of NbS implementation underscore their potential, as showcased in the diverse applications and success stories associated with these approaches.

In Copenhagen and Singapore, green roofs and permeable surfaces have become integral components of urban development strategies. Copenhagen's extensive green roof initiatives have transformed building rooftops into vibrant ecosystems, contributing to temperature regulation, carbon sequestration, and enhanced biodiversity. Similarly, Singapore integrates green roofs and permeable surfaces as part of its commitment to sustainable urban development. These applications effectively manage stormwater, reduce heat, and contribute to overall urban resilience[39,40].

Curitiba, a city in Brazil, stands out as a pioneer in successful urban forestry programs[41]. The city's strategic tree planting, creation of green belts, and preservation of natural areas contribute not only to carbon sequestration but also enhance biodiversity, improve air quality, and provide recreational spaces for residents. Curitiba's approach exemplifies the integration of NbS to create a sustainable and resilient urban environment.

Seoul's Cheonggyecheon restoration project represents another impactful NbS initiative[42]. By removing an elevated highway to uncover and restore an urban stream, the project focused on ecological and recreational benefits. This transformation turned the area into a vibrant public space with natural water features, illustrating how NbS can be applied to restore natural ecosystems within urban settings, providing both environmental and social benefits.

In the United States, Portland, Oregon, showcases the use of green infrastructure, including eco-roofs and permeable pavements, to manage stormwater and mitigate urban heat island effects. Portland's commitment to sustainable urban planning has made it a model for integrating NbS into city development[43].

Furthermore, the city of Melbourne, Australia, has implemented extensive urban greening initiatives, including the creation of green corridors and public parks[44]. These efforts aim to enhance biodiversity, provide recreational spaces, and improve overall urban well-being, demonstrating the versatility of NbS in different geographic and cultural contexts.

These examples collectively emphasize the potential of NbS in addressing climate change impacts in urban areas. Whether through green infrastructure, urban forestry programs, water restoration projects, or expansive urban greening initiatives, cities worldwide are leveraging NbS to enhance sustainability, resilience, and the overall quality of urban life. While NbS offers substantial benefits, limitations exist. The implementation of NbS faces significant challenges, including economic considerations such as initial costs and maintenance, social issues related to equity in access, and political barriers in urban policies. The time required for ecosystem establishment and potential conflicts with existing infrastructure are also notable challenges, requiring adaptive strategies and cross-sector collaboration to overcome them.

The implementation of green roofs and permeable surfaces may be constrained by available space, particularly in densely populated urban areas. Additionally, the initial costs for installation and maintenance can be prohibitive. Technical challenges related to integrating these structures into existing buildings may arise, including issues of weight, drainage, and waterproofing. The effectiveness of these solutions can vary depending on local climatic and urban conditions, limiting their universal applicability. The absence of government policies encouraging or subsidizing the implementation of these solutions can pose a significant obstacle. Inflexible urban planning regulations may also hinder the adoption of these technologies.

Urban forestry programs require ongoing maintenance and may face long-term sustainability challenges, such as pests and diseases. The expansion of urban green areas could conflict with other land-use needs, such as housing and commercial development. Urban forestry may not be prioritized on political agendas, especially when other urban issues, like housing and infrastructure, dominate the political landscape.

Ecosystem restoration projects are complex and may incur high implementation and maintenance costs. Such projects could lead to the displacement of existing communities and businesses, raising social equity concerns. They can also be affected by political disputes, changes in government administrations, and bureaucratic delays, impacting their continuity and effectiveness.

In regions with extreme weather events, these solutions may not be sufficient, requiring combination with more robust engineering solutions. Integrating green infrastructure in an already developed urban environment can be challenging due to existing infrastructure and planning constraints.

The maintenance of green corridors and urban parks is crucial for their effectiveness, and there may be challenges in maintaining biological diversity in these areas. While such initiatives improve local quality of life, their impact on the climate on a larger scale may be limited.

NbS may also encounter obstacles related to general policies, such as:

- Changes in administration or policies could lead to a lack of consistency in supporting green infrastructure projects;
- political resistance to the expansion of green areas due to development pressures and real estate interests;
- Limited government budgets or reallocation of funds could restrict adequate financing for NbS;
- lack of coordination and collaboration among different governmental departments and administrative levels;
- Conservative policies or resistance to changes in established practices may be an obstacle to the adoption of innovative NbS;
- inequity and social injustice, NbS may not meet the needs of low-income communities or may contribute to gentrification.

Table 2 summarizes the key aspects of NbS in terms of their contribution to climate change mitigation, technical and political issues.

To advance the field of NbS, future research should focus on quantifying specific benefits in different urban contexts, exploring methodologies for integrating green infrastructure into existing urban environments, and assessing the impact of these solutions on marginalized low-income communities to ensure a fair distribution of benefits. It is crucial to integrate insights from urban planning, sociology, and economics. For example, urban planning can provide strategies for effectively incorporating green infrastructure in dense cities, while sociology can illuminate how these solutions affect different social groups.

Table 2. NbS for climate change mitigation: challenges, potential and limitations.

NbS	Potential applications	Technical limitations	Political challenges	Social impacts	Economic implications
Green walls	regulating local microclimate, promoting biodiversity	space constraints, integration challenges in existing buildings	lack of incentivizing policies, inflexible urban regulations	Social equity and accessibility issues	Initial and maintenance costs
Permeable pavements	reducing surface runoff, aiding in groundwater recharge	installation and maintenance costs	competing land-use needs, lower priority in political agendas	Impacts on water quality and community health	Savings in stormwater management
Urban forests	carbon sequestration, cooling effects, fostering biodiversity	maintenance requirements, susceptibility to pests and diseases	social displacement and bureaucratic changes	Benefits for public health and well-being	Reduction in health and energy costs
Eco-roofs	managing stormwater, mitigating urban heat island effects	challenges in integration due to existing infrastructure	fragmented governance, inconsistent support	Improved air quality and green space	Increase in property value
Greening initiatives	enhancing biodiversity, providing recreational spaces	maintenance, limited impact in large-scale climate change	resistance due to development pressures	Green spaces for recreation and leisure	Tourism and commercial attraction benefits

The intricate relationship between urbanization, climate change, and the imperative need for sustainable solutions necessitates a comprehensive understanding of the role of urban green infrastructure as NbS for climate change mitigation. The global examples of NbS implementation, from Copenhagen and Singapore to Curitiba and Melbourne, underscore the versatility and applicability of these solutions in diverse urban settings. While acknowledging the substantial benefits of NbS, the article also recognizes the existing challenges and emphasizes the importance of strategic integration with conventional solutions for a comprehensive approach. In essence, this opinion article serves as a call to action for researchers, urban planners, and policymakers to recognize the significance of NbS for climate change mitigation.

In conclusion, this opinion article has explored the multifaceted challenges and mechanisms through which NbS enhances urban resilience and contributes to the overarching goal of mitigating climate change impacts in urban settings. NbS must be adapted to diverse socioeconomic and cultural contexts, considering equity issues in implementation. This includes ensuring that vulnerable communities benefit from green infrastructure and that these solutions do not contribute to the gentrification of urban neighborhoods.

Author contributions

Conceptualization, AB and LCdCM; data curation, AB; formal analysis, RGN and LCdCM; investigation, RGN; methodology, AB; project administration, AB and LCdCM; Resources, RGN; software, RGN; validation, AB; writing—original draft, RGN, AB and LCdCM; writing—review and editing, AB. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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