



Nature-based solutions for urban climate resilience: implementation, contribution, and effectiveness

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ABSTRACT

Driven by the need to enhance urban climate resilience, there is a growing preference for nature-based solutions (NbS) over conventional architecture, mostly attributed to their ecological benefits and economic advantages. This systematic review analyzed global knowledge and research gaps regarding the implementation, contribution, and effectiveness (ICE) of NbS. Using Publish and Perish version 8 software, across Google Scholar and Elsevier Scopus, 749 publications were initially retrieved (2014 – 2025), with 84 (11.20 % of the initial search results) meeting inclusion criteria. Additionally, a qualitative analysis was conducted on a sample of 26 publications, selected from the initial 84 articles. The review demonstrates that though NbS hold substantial promise for optimizing urban climate resilience, their successful implementation is contingent upon addressing a complex relationship between factors like data-driven planning, stakeholder awareness and engagement, resource availability, institutional framework, and context-specific considerations. Moreover, it highlights the significance of integrating ecological, economic, and social dimensions, tailoring interventions to local needs, and utilizing rigorous evaluation methodologies to ensure the effectiveness and long-term contribution of NbS in fostering resilient urban environments to the climate change impacts. Though the scope of this review was constrained by various factors like language and database, it identified significant research gaps, including limited geographical case studies, reliance on secondary data and sources, methodological inconsistencies, lack of standardized approaches, and inadequate understanding of the complex functions of NbS in urban climate resilience. For instance, of the 26 qualitative sample publications selected for this systematic review, almost 54 % employed only secondary data sources, and eight publications lacked clear and specified data analysis techniques. Hence, future research should prioritize primary data, robust methodologies, transdisciplinary collaboration, and a broader geographical focus to promote the effectiveness and successful implementation of NbS.

Introduction

Urban ecosystems often suffer from rapid urbanization and global change, leading to environmental degradation, increased pollution, and ecosystem services disruption [1,2]. Urbanization causes habitat loss and fragmentation, threatening biodiversity and the ecological processes that support urban ecosystems [3,4]. The current environmental stresses in urban areas also aggravate these challenges, demanding integrated solutions that address both ecological and social dimensions [5].

Cities must become resilient to climate-related hazards/shocks. The

concept of resilience is far more important than addressing climate hazards/shocks, for it involves adapting urban systems to endure future climate impacts. To ensure comprehensive risk management, integrating resilience strategies with urban development and sustainability efforts is mandatory [6]. However, it is a complex process that requires multiple stakeholders such as local governments, communities, and institutions. To develop practical and locally relevant adaptation measures, collaboration and shared learning among these stakeholders is required [7]. Involving communities in resilience-building efforts promotes public support and engagement, ensuring adaptation strategies more effective and sustainable.

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Establishing operational frameworks for urban climate resilience is also critical for planning and development. The frameworks help planning practitioners convert theoretical concepts of resilience into actionable strategies that can be tailored to local situation [8]. Cities can establish rigorous plans to optimize their resilience to climate change, by emphasizing the characteristics of urban systems, the roles of agents, and institutional linkages [9]. Strengthening the skills and knowledge of urban planners and managers, and excelling multi-level governance to support resilience initiatives. Capacity building is, therefore, vital for empowering cities to transition towards resilience in the face of high complexity and uncertainty [10].

Nature-based solutions (NbS) are becoming a vital approach to reimagining urban landscapes, providing ecological and socio-economic benefits. They integrate natural components into urban planning to overcome environmental, economic, and social issues, enhancing urban sustainability and resilience [11]. Nature-based solutions are multidimensional interventions to simultaneously address economic, social, and ecological sustainability challenges. They provide a wide array of interventions relative to traditional approaches, with a major focus on offering solutions to complex urban issues [12]. Nature-based solutions are adaptable tools that optimize the capacity of landscapes and cities to address critical social, economic, and environmental challenges [13].

Nasrabadi [14] suggest that NbS contribute to urban landscape sustainability by enhancing ecological indicators like biodiversity, air, water, and soil. Moreover, NbS also improve socio-cultural aspects such as security, health, education, and social relationships, in addition to economic dimensions, including green jobs, urban tourism, and waste management [14]. These enable cities to better adapt to climate change and other urban stresses, fostering urban resilience [11,15].

Nature-based solutions are deliberated to improve ecological metrics like species diversity and ecosystem functionality and health [16,17]. The economic valuation of NbS like urban green spaces, demonstrates that the public is willing to pay for biodiversity benefits, highlighting that the economic benefits of implementing NbS can surpass the costs [18]. This proposes that NbS can provide net economic benefits, qualifying their implementation in urban planning. Integrating NbS into urban development planning and policies is crucial to maximize their benefits and ensure sustainable urban development.

As demonstrated in case studies like in Rescaldina, Italy, urban planning can benefit from integrating ecosystem services into spatial planning regulations [19]. Such an approach improves the performance of urban ecosystems by employing NbS as greening design actions.

Moreover, by promoting ecosystem services and generating social, economic, and environmental co-benefits, NbS contribute to efforts and progresses towards achieving sustainable development goals (SDGs) [20]. However, there is a lack of sufficient empirical evidence that support the assumed co-benefits of NbS, which hinders their effective integration into urban planning. Thus, more research is required to understand the trade-offs and synergies of NbS implementation [17,21]. Addressing research gaps and improving socio-ecological outcomes enhance the effectiveness of NbS in creating sustainable urban environments.

The objective of this review paper is to broadly analyze the implementation, contribution, and effectiveness (ICE) of NbS for urban climate resilience. The review seeks to answer specific questions, including what are the major socio-economic and governance issues, and enabling factors affecting the successful implementation of various NbS in different urban context (RQ1)? to what extent and through which mechanisms do specific NbS contribute to addressing climate-related challenges and ensuring urban climate resilience (RQ2)? how can the long-term effectiveness of NbS for urban climate resilience be measured and monitored, and what are the possible approaches for evaluating their integrated ecological, social, and economic impacts (RQ3)?

Theoretical framework

Nature-based solutions are multipurpose to address multiple urban challenges such as climate impacts, biodiversity loss, and public health. They are important in urban adaptation strategies, particularly in developing countries where complex technological interventions are less preferred over self-reliant solutions [22,23]. Urban planning is crucial in implementing NbS by managing trade-offs and conflicts throughout spatial, temporal, and social equity dimensions [11]. Nevertheless, the implementation of NbS is still limited, demanding increased awareness and cooperation among stakeholders (Fig. 1), including citizens, urban planners, and policy-makers [24].

Nature-based solutions have proved potential in addressing climate impacts and ensuring urban resilience. Particularly in natural or semi-natural ecosystems, NbS are often as effective or more so than alternative interventions [25]. However, challenges, including the need for stronger evidence on their effectiveness, governance challenges, and the integration of socio-environmental justice in their implementation remain [26,27]. Significant knowledge gaps also observed, including but not limited to the need for site-specific design criteria and assessments of

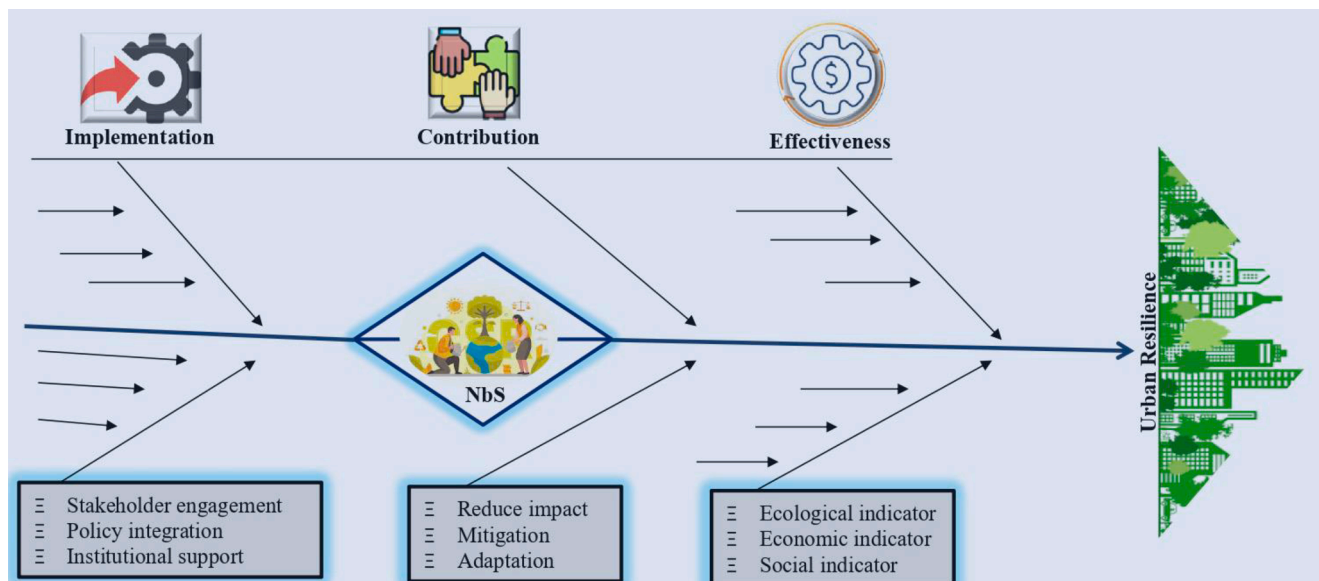


Fig. 1. The review theoretical framework depicting major components of ICE of NbS towards ensuring urban resilience.

cost-effectiveness [23,28].

Materials and methods

The review utilized a mixed-methods systematic review approach, combining quantitative and qualitative analyses, to synthesize existing studies on the potential of NbS to optimize urban climate resilience. The purpose of this systematic review was to comprehensively analyze the implementation, contribution, and effectiveness (ICE) of NbS for urban climate resilience. With this regard, the review mapped current knowledge, recognized research gaps, and suggested future research directions.

The systematic review synthesized scientific evidence on ICE of NbS following a pre-defined protocol by Major [29] and established methodologies and protocols by Tacconelli [30] and Moher et al. [31]. The review involved four essential steps, including selection criteria, search procedure, data collection, and presentation.

Article search strategy

The review was conducted between January 2025 and March 2025. Article inclusion criteria were narrowed using specific filters, but publication year as a limiting factor is exception, to manage the scope of the review. Preliminary searches showed that publication year would not substantially impact the comprehensiveness of the review. Two databases, Google Scholar, and Elsevier Scopus were searched to examine the extent of global literature on the ICE of NbS using Publish or Perish version 8 software. Similarly, search terms were applied to article titles, abstracts, and keywords using Boolean operators, specifically "AND" and "OR". Moreover, VOSviewer version 1.6.20 software was utilized to map keyword densities, portraying essential research topics in NbS and climate resilience within the context of urban environment.

In Google Scholar database, search strings like "nature-based solutions" AND "urban climate resilience" OR "NbS implementation" AND "NbS contribution" AND "NbS effectiveness" AND "urban park" OR "urban forest" AND "green infrastructure" were used. Search strings such as "nature-based solutions" OR "urban policy" AND "climate resilience" AND "NbS effectiveness" OR "NbS implementation" OR "NbS contribution" AND "ecosystem service" AND "climate change" OR "mitigation" AND "adaptation" were used in Scopus database. Accordingly, a total of 749 articles were acquired from both databases.

Article selection procedure

Nineteen duplicate entries were removed using CADIMA software version 2.2.4.2. from the initial search results of 749 articles. Selection criteria (Table 1) were applied to ensure alignment with the review's objectives, considering information, including author, journal citation report (JCR), journal name, publication year, geographic area, research focus, and methodology (Table 1) based on criteria adapted from Guitart et al. [32] and Jellason et al. [33]. Taking the scope of the review into account (Table 1), 546 articles were excluded as being outside the scope

of the review, after careful screening the titles, abstracts, and keywords of 730 articles. The quantitative analysis, thus, ultimately incorporated 84 research publications, accounting for 11.20 % of the initial search results. The 84 publications were then read in full.

Data analysis

The review employed a mixed-methods to analyze the ICE of NbS to enhance urban climate resilience and identify possible research gaps. The quantitative analysis involved 84 publications. Simultaneously qualitative analysis was conducted on a sample of 26 of these publications. The smaller sample size for the qualitative analysis demonstrates a focus on studies employing qualitative methodologies that particularly assessed ICE of NbS (Appendix A), following structured approach by Gonçalves et al. [34]. The quantitative analysis extracted data on publication year, most cited articles, journal citation counts, keyword co-occurrences and clouds, and geographic area. Most importantly, the review prioritized empirical studies employing quantitative methodologies.

Results

This section presents the review quantitative and qualitative analyses results. The quantitative analysis involves research productivity over time, key databases, highly cited articles, articles origin, keyword trends, and geographic locations. Conversely, qualitative analysis focuses on the methodologies used in the empirical studies and their key findings.

Quantitative analysis

In the first step, two databases were searched for relevant articles using Publish or Perish version 8 software (Fig. 2). In the second step, quantitative data analysis was performed to map the scientific output associated with NbS potential to optimize urban climate resilience, focusing on ICE, a critical aspect of NbS. This quantitative analysis was carried out using a sample of 84 publications.

Fig. 3 depicts a non-linear trend in NbS sample publications and associated issues over a 12-year period. A significant increase was observed in publications between 2017 and 2021, followed by a slump in 2022. Post-2022, publication numbers showed fluctuating trend. In general, recent years highlight a growing interest in NbS, specifically regarding complex ICE systems. This surge in research is attributed to growing global concerns of climate change, and the need for climate resilience. The escalating research and publication trend coincides with major climate change agreements like the Paris Agreement [35], demonstrating the increasing importance of NbS as a solution for climate adaptation and mitigation.

Fig. 4 represents the databases distribution of screened NbS publications. Accordingly, Google Scholar was the major source, representing 61 % of the publications, while Elsevier Scopus contributed 39 %.

The top 10 most cited articles were identified from the 84 articles reviewed (Table 2). The most highly cited paper, by Kabisch et al. [26], was published in Ecology and Society Journal in 2016. This shows that the citation count is not affected by the publication year. For instance, a 2014 paper received 292 citations, but 2022 obtained 625, highlighting that earlier publications are not inherently more cited than later ones.

All the articles selected for the review were mapped to understand the geographical focus of NbS within both databases. Fig. 5 represents a global emphasis on NbS and its essential aspects, ICE in urban climate resilience. Notably, Italy stands out with the highest concentration of studies (five articles), followed by UK (four articles). This associated with the emergence of NbS as a priority area for the European Union's (EU) Horizon 2020 Research and Innovation Policy agenda [36] since 2015, contributing to the concept of NbS to obtain more research attention and policy integration.

Table 1
Inclusion and exclusion criteria for articles.

Criteria	Excluded	Included	Objective
Article type	Non-indexed articles	Peer-reviewed archrivals	Original research findings
Availability	Non-open access	Open-access articles	Accessibility, free of use
Year	Before 2014	2014 - 2025	Generate latest information
Theme	Outside the scope	Articles on ICE of NbS	Maintain the target
Language	Not written in English	Written in English	Language proficiency

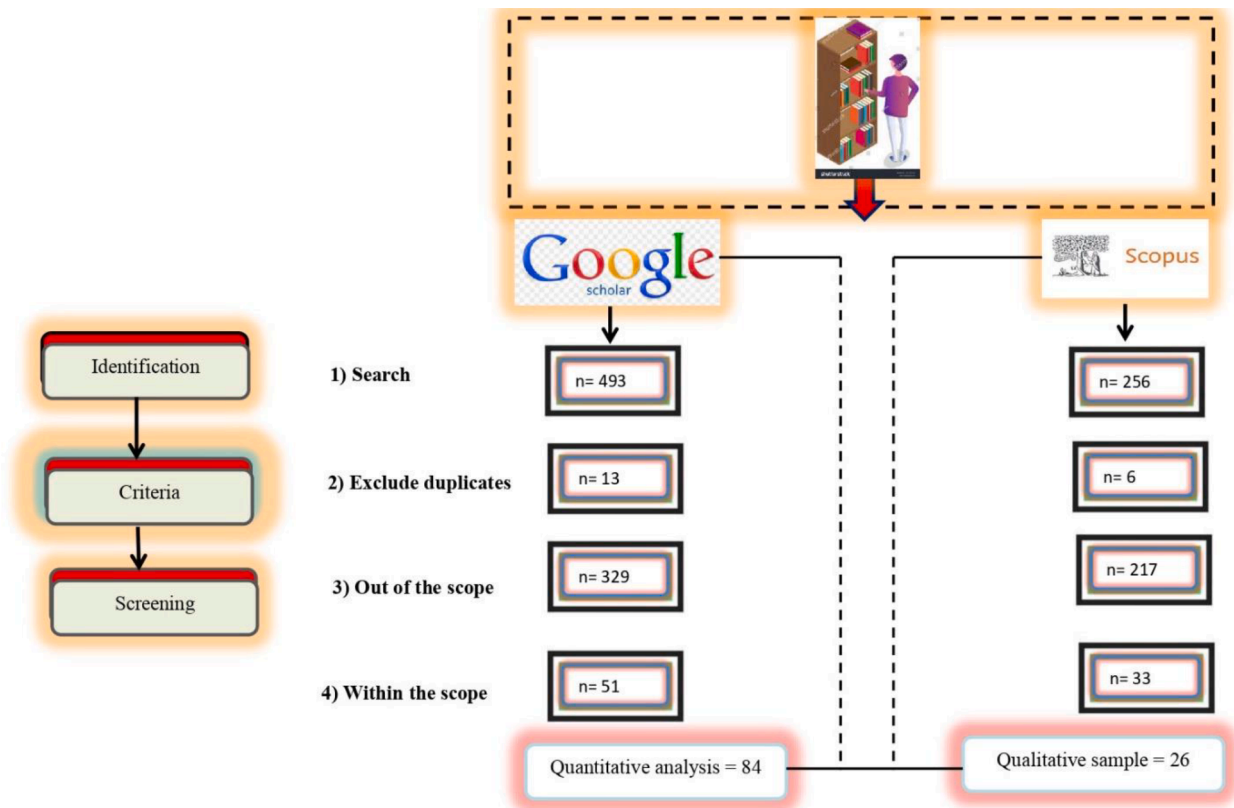


Fig. 2. Sample selection protocol.

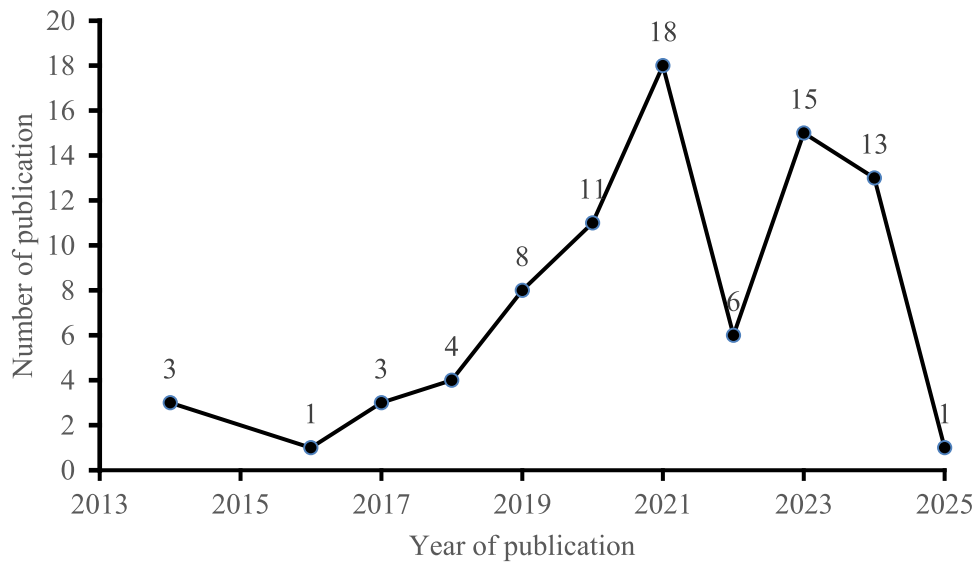


Fig. 3. Number of selected articles per year from 2014 – 2025.

Between 2014 and 2025 (Fig. 6), research emphasized cities, urban parks, green spaces, urban policy, ecological sustainability, institutional support, urban sustainability, storm water, and disaster risk reduction. Recurring keywords throughout studies demonstrate the persistent importance of NbS-related topics like NbS intervention, local community, green infrastructure, urban environment, climate change mitigation, and climate resilience. Moreover, NbS implementation, contribution, and effectiveness emerged as crucial areas of interest.

However, the relative size of the circles in Fig. 6 shows that though topics such as NbS implementation, contribution, and effectiveness are

gaining attention, they still represent a smaller proportion of overall research relative to more established areas. This highlights that these growing topics, though essential, are rather novel within NbS and climate resilience, and substantial theoretical gaps remain. Demonstrating the relative emphasis placed on each area, the circle sizes serve as a visual approximation of the volume of research dedicated to each topic.

The analysis identified three keyword clusters, each represented by a distinct color (Fig. 7). The analysis considered keywords that appeared 20 or more times, with the occurrence value representing the frequency

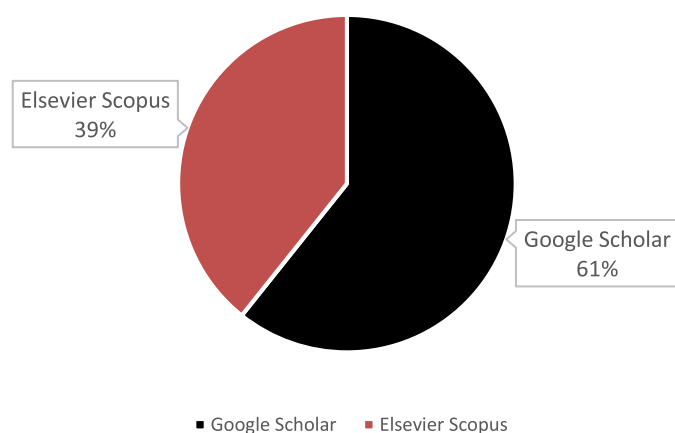


Fig. 4. Number of selected articles per database from 2014 – 2025.

Table 2
Top 10 articles with the highest number of citations.

Article Title	Journal	Year	Cited by
Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action	Ecology and Society	2016	1557
A framework for urban climate resilience	Climate and Development	2012	975
Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa	Landscape and Urban Planning	2014	763
Nature-based solutions for climate change adaptation are not located where they are most needed across the Alps	Regional Environmental Change	2022	625
Mapping the effectiveness of nature-based solutions for climate change adaptation	Global Change Biology	2020	555
Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making	BioScience	2019	503
Building urban resilience with nature-based solutions: How can urban planning contribute?	Cities	2019	481
Nature-based solutions for resilient landscapes and cities	Environmental research	2018	475
Urban greening through nature-based solutions – Key characteristics of an emerging concept	Sustainable Cities and Society	2019	399
Ecosystem Services in Urban Landscapes: Practical Applications and Governance Implications	Ambio	2014	292

of use. Accordingly, the keywords fall into three thematic groups, including challenges, solutions, and effects.

Qualitative analysis

A qualitative analysis was performed on a sample of 26 publications, chosen from the initial 84 articles. The selection considered strict inclusion criteria, most importantly, empirical studies had to employ exclusively quantitative metrics to measure (1) NbS implementation, (2) NbS contribution, and (3) NbS effectiveness (Appendix A). This focused sample offered an in-depth exploration of NbS, an emerging approach with potential to contribute to optimizing urban climate resilience. The following sections, hence, will discuss empirical findings from these 26 publications, addressing the critical review questions, through the lens

of the urban climate resilience.

Analysis of implementation of NbS for urban climate resilience

This analysis considered 11 articles (Appendix A) that quantitatively investigated the possibilities and challenges to successfully implement NbS for urban climate resilience. The studies utilized statistical metrics. For example, Velayo et al. [37] assessed awareness, perception, and willingness regarding NbS and climate change among stakeholders in Iligan City, Philippines, using survey questionnaires, demographic profile sheets, and stakeholder interviews. The study found that substantial differences were observed in awareness and perceptions across the distinct socio-economic backgrounds of stakeholders, highlighting higher education and income levels showed greater awareness, perception, and willingness to engage in NbS practices.

To understand how data-driven science can inform the integration of NbS into cities, Sari et al. [38] used a dynamic and adaptive social acceptance framework for developing questionnaires to collect primary data. The study also utilized behavioral theories and case studies to indicate how to utilize data-driven science to integrate and upscale different NbS into cities. The study identified procedural and distributive fairness, costs and benefits, perceived risks, experience, knowledge, and personal norms as major factors affecting social acceptance of NbS. The study utilized data-driven strategy to better understand the varied perspectives of different communities and tailor the implementation of NbS to reflect these differences.

Between 2019 and 2020, Voskamp et al. [39] conducted interviews with municipal officers from eleven European cities, focused on barriers to NbS uptake, the role and application of NbS tools, and desired outcomes from NbS tools, alongside two workshops. The tools were analyzed on their descriptive characteristics and potential fields of application. Accordingly, the study identified four critical challenges the municipal officers face with NbS uptake, including resources availability, institutional setting, level of expertise, know-how or competence, and collaborative governance and planning.

The study focused on the co-learning process outputs based on ecosystem-based adaptation and NbS for disaster and risk reduction (DDR) was conducted by Young et al. [40] in São Paulo state, Brazil. The surveys involve knowledge maps, Workshop Mobilization for Organization and Feasibility of Resilient Urban Spaces (MOVER), and document analysis. The research reports existing measures are inadequate in their ecological focus regarding DRR and the benefits they provide. Additionally, a more detailed approach is required to support NbS and its systematic mainstreaming. Moreover, it suggests an operational definition to specify how NbS can be integrated in local planning to ensure an effective and meaningful implementation.

In Kumasi, Ghana, an urbanized area known for its commercial and industrial activities, Boateng et al. [41] conducted study focused on enabling NbS in Asokwa municipality. To collect primary data, the study utilized 367 household surveys and seven agency interviews. Thematic analysis was used to analysis the data. It was found that though local communities acknowledged the importance of NbS, barriers like poor consideration of natural infrastructure in planning, high costs of NbS interventions, limited technical capacity, and disparate interests from various institutions hinder NbS implementation. The study concluded that scaling up NbS in urban ecosystems needs main investments, tailoring the specific needs of each city.

Glytsos et al. [42] simulated the expected benefits of small-scale NbS implementation in Chania city center. A green roof and green wall were planned for installation at a municipal car park in a concrete-dominated area of the city center. The study examined the expected benefits of the planned installations, including microclimate regulation, carbon sequestration, thermal comfort, air filtration, and aesthetic values. To simulate the microclimate and thermal comfort impacts of the interventions, ENVI-met software was used, with (10) existing conditions (“no green” scenario), (2) green wall implementation, (3) green roof

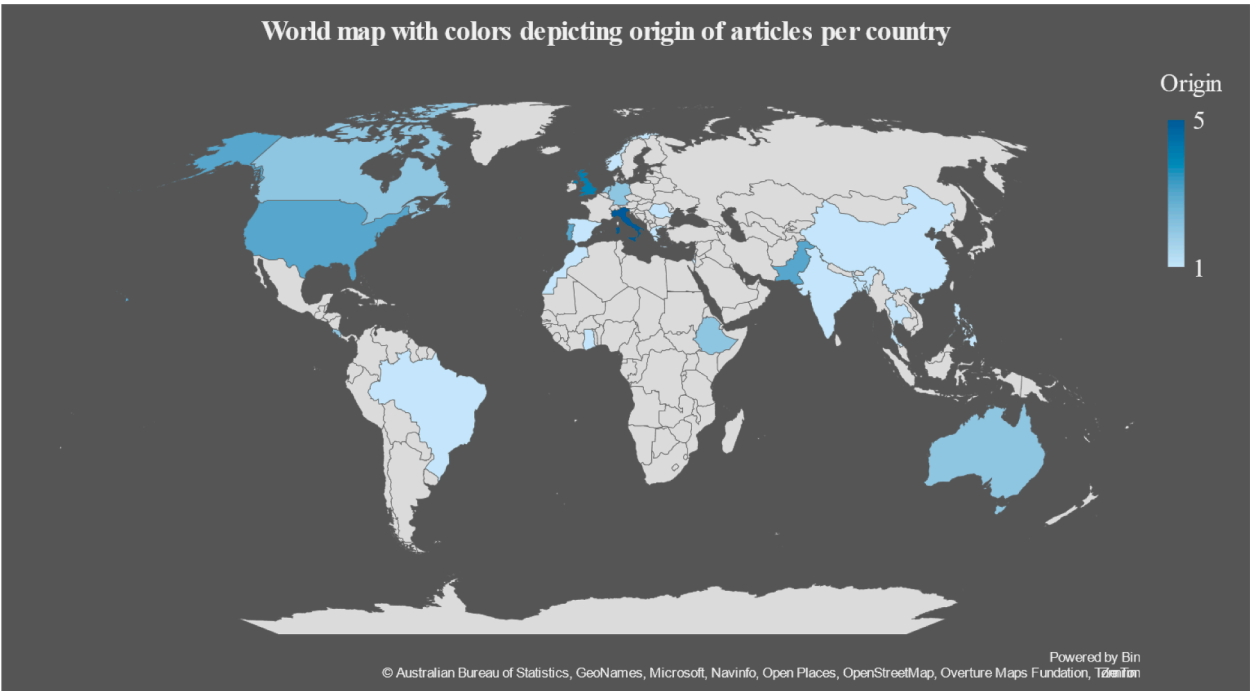


Fig. 5. Number of articles included in the review based on country of origin ($n = 84$).

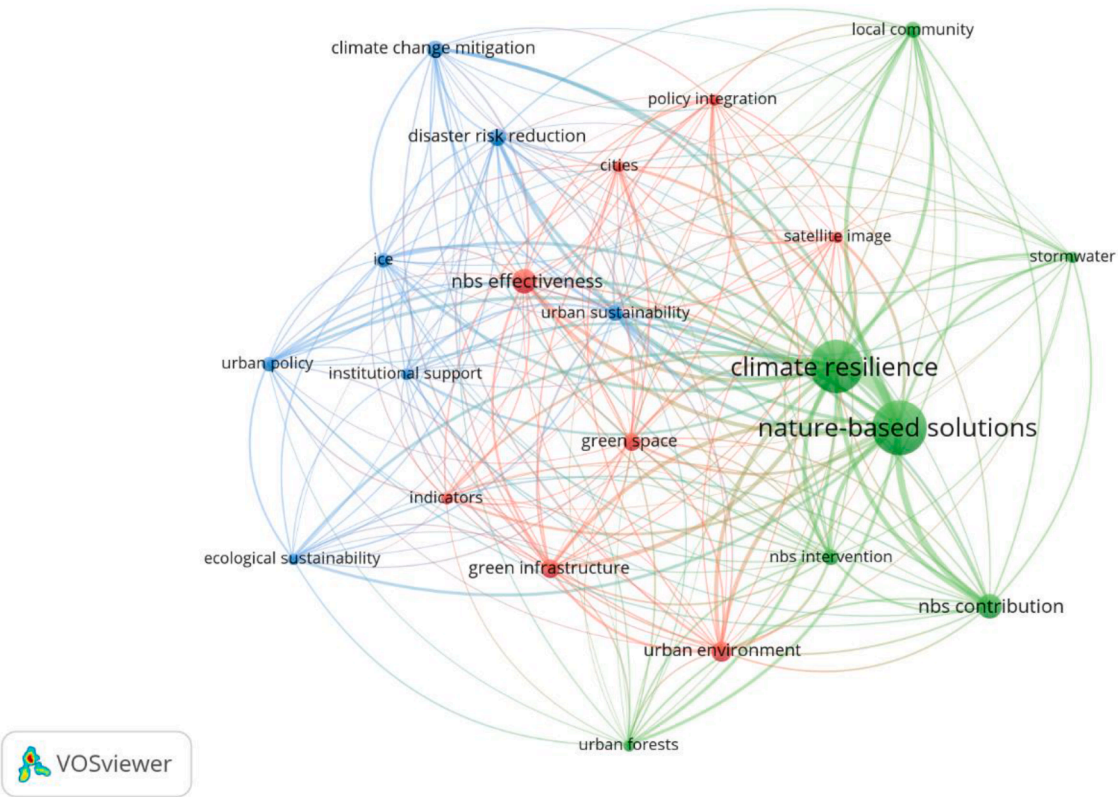


Fig. 6. Keyword density, representing major areas of research topics of NbS and climate resilience.

implementation, and (4) integrated green wall and green roof implementation. The green wall was modelled as modular system of combining plants, whereas green roof with small urban trees and shrubs of defined characteristics based on available data. The carbon storage potential of the green wall and green roof was measured based on literature values for Mediterranean shrublands and green roof shrubs.

The findings demonstrated that the green wall area contributes the most to carbon sequestration, while the green roof contributes the most to microclimate regulation. The use of NbS in 44 large Polish cities to adapt to climate change and energy transformation, was analyzed by Pancewicz et al. [43], in comparison to the URBAN GreenUP project. The 44 Polish cities that

Clusters	Keywords	Occurrences	Content theme
Cluster 1	nbs effectiveness	94	
	urban environment	64	
	green infrastructure	60	
	green space	51	
	cities	23	
	indicators	23	
	satellite image	23	
Cluster 2	nature-based solutions	449	
	climate resilience	442	
	nbs contribution	100	
	nbs intervention	44	
	local community	43	
	storm water	24	
	urban forests	22	
Cluster 3	climate change mitigation	51	
	disaster risk reduction	45	
	urban sustainability	44	
	urban policy	36	
	ice	32	
	ecological sustainability	25	
	institutional support	22	

Fig. 7. Keywords cluster analysis based on co-occurrence analysis results, with color of the content theme: blue denotes challenge; green denotes solution; and black denotes effect ($\pm$).

participated in the Ministry of Environment project "Development of Urban Adaptation Plans for Cities with >100,000 residents in Poland" implemented in 2017–2019, was a major source of data. Local strategic documents, national programs, civic budgets, municipal websites, and Urban Adaptation Plans (UAPs) were considered key sources of data. The spatial solutions studied were categorized into three groups, mainly re-naturing urbanization, water interventions, and singular green infrastructure activities. It was then concluded that the results of the study can be used to optimize the knowledge on the links between NbS planning in adaptation activities and implementation.

In Alpine Convention space area, Austria, Italy, France, Switzerland, Germany, Slovenia, Liechtenstein, and Monaco, Dubo et al. [44] identified NbS for climate change adaptation via databases, including ClimateADAPT, Oppla, and PHUSICOS, and environmental agencies websites associated with forestry, freshwater, agriculture, biodiversity, and protected areas. The climate change impacts addressed by NbS or impacts worsened by climate change like loss of biodiversity, were targeted inclusion criteria. Accordingly, NbS was grouped as (1) on-the-ground, (2) enabling, and (3) mixed. Potential climatic hazards tackled by each NbS and the nature's contributions to people (NCP) they address were coded using the modified Díaz et al. [45] classification for mountain regions. To compare NbS locations, spatial analysis was performed, considering current and future climate change hazards like temperature, precipitation, heatwaves, flood hazards, snow cover, and wildlife; NCP indicators such as NCP supply, flow, flow-supply ratios, and demand-supply ratios; and combinations of hazards and NCP indicators. Accordingly, the locations of NbS are not entirely associated with the current supply-flow-demand indicators of most NCP, nor to the

hazards' intensity. Nature-based solutions do not match higher values for NCP indicators, but located in areas where drought and flood hazards are more intense. Regardless of the intensity of hazards, NbS intending to produce wood and offer productive function again landslides are located in areas with greater levels of NCP. In general, the study suggested that NCP indicators and hazards are not the major drivers of NbS implementation. Thus, integrating present NCP flows and local climate conditions is required to support a macro-regional strategy for NbS implementation planning [44].

Simperler et al. [46] spatially analyzed the compatibility of implementing NbS for reducing urban heat islands (UHI) and stormwater pollution in Berlin, Germany. The UHI effect data were collected from a publicly available climate analysis map, classifying UHI intensity at the block/street section level into four groups, non-existent, weak, medium, and strong. Likewise, data on the stormwater pollution were obtained from a comprehensive monitoring program of stormwater runoff in five catchments in Berlin. Over 100 organic and inorganic trace pollutants were analyzed by the program. For the sake of analysis, the spatial distribution of average annual pollution loads was compared with UHI hotspots. The pollution distribution load over the four groups of UHI was visually analyzed using boxplots. To analyze the relationship between the UHI effect and stormwater pollution load of the individual parameters, a linear regression with a linear model was conducted. The criteria were divided into two groups, namely "high" and "low" to analyze the spatial matching of high UHI and high stormwater pollution. The findings indicated for any parameter, pollution load and the UHI effect showed no linear relationship. It stated that nearly 2270 building/street sections showed matching of high UHI and high stormwater pollution

loads, out of 14,000. Moreover, stormwater pollution was high for three out of the four parameters, in the majority of building/street sections. Overall, the study concluded, for both challenges, the compatibility of NbS implementation depends on the implementation strategies for NbS and specific NbS measures,

An online survey was carried out in the Veneto region, northeastern Italy, by Bernello et al. [47] to explore people's knowledge and perception of NbS for flood mitigation. Using convenience sampling, the survey link was shared through email and social networks. Questions regarding territorial features, general risk perception, knowledge and perceived effectiveness of NbS, and willingness to implement NbS were incorporated into survey. The ordinal logistic regression was employed to analyze the data. The study pointed out a significant relationship between previous knowledge of water management systems and the perceived effectiveness of some NbS. It was found the perceived effectiveness of NbS has also found to be affected by level of connection with the territory.

In Ostrava and Upper Silesian agglomeration, Vojvodíková et al. [48] conducted research to identify which elements of NbS are perceived as dangerous and if personal experience and active consultation may affect these perceptions. Encompassing parts of Poland (Upper Silesian agglomeration) and the Czech Republic (Ostrava), this region shares a coal mining and industrial history. A questionnaire survey was carried out about specific elements of NbS without discussing particular locations in Ostrava, and the feelings of inhabitants regarding specific NbS were surveyed at particular locations utilizing guided interviews in Upper Silesian agglomeration. Accordingly, both questionnaire in Ostrava and interviews in Upper Silesian agglomeration led to the identification of elements of concern. The study suggested participants who discussed a specific location had a better understanding of the urban situation and were less concerned. Furthermore, it underscored both questionnaire and interviews highlighted the communication requirement with inhabitants before confirming the design of a specific NbS and the desirability of discussing site-specific issues with citizens.

Thus, the stakeholder awareness, perception, and willingness to adopt NbS are positively correlated with higher education and income levels, while procedural fairness, perceived risks, and personal norms significantly influence social acceptance. While local communities often recognize the value of NbS, obstacles such as high costs, inadequate integration of natural infrastructure in planning, and misaligned interests persist. Spatial analyses demonstrate that the placement of NbS does not always align with areas of greatest need or hazard intensity, suggesting a need for more data-driven, context-specific planning. Moreover, studies underscore the importance of public engagement, tailored communication, and co-learning processes to address concerns and enhance the effectiveness of NbS interventions. To sum up, successful scaling and mainstreaming of NbS in urban environments require targeted investments, adaptive strategies, and stronger integration of local knowledge and climate conditions into planning and decision-making processes.

Analysis of contributions of NbS to urban climate resilience

Of the 84 articles analyzed, six focused on contributions of NbS to urban climate resilience. The subsequent paragraphs offer a snapshot of these studies. Collectively, these studies underscore NbS's potential in addressing diverse urban challenges while highlighting the need for standardized evaluation frameworks and balanced, long-term resilience strategies. Accordingly, Beceiro et al. [49] developed Resilience Assessment Framework (RAF) construction for six European cities and Vancouver, Canada to evaluate the contribution of NbS to urban resilience, with a major focus on stormwater management and control. The framework was developed based on the ISO 24,500 standards for water supply and wastewater management system, with defined objectives, criteria, and metrics. On top of that, stakeholder opinion was employed to analyze the relevance and applicability of metrics to cities. A

multidimensional and comprehensive RAF was proposed to measure the contribution of NbS to urban resilience, focusing on stormwater management and control. The framework integrates features for urban resilience evaluation and critical aspects of NbS assessment, driven by resilience objectives and evaluation criteria.

Likewise, Conti et al. [50] analyzed the contribution of NbS in fostering sustainable cities through resilience thinking, emphasized NbS projects being implemented in Lucca and Latina, a medium-sized Italian cities with different historical backgrounds but share socio-economic and institutional similarities. It utilized a qualitative case study approach, exploring the NbS projects in both cities to cultivate lessons for enhancing sustainable cities. It was found that NbS initiatives in both cities optimized the well-being of citizens and enhanced sustainable urban development, demonstrating the potential of NbS to promote urban resilience.

At global scale, Goodwin et al. [51] analyzed a dataset of 750 indicators from 74 NbS projects in 61 cities across 40 countries. Literature reviews and assessments of information and processes used for measuring urban NbS for resilience were integrated with interviews of 15 local actors to collect the data. Mixed-method and interdisciplinary approach were used to analyze current evaluation practices. The study points out that the NbS projects do not sufficiently balance climate adaptation with other goals, such as biodiversity conservation and socio-economic challenges. Additionally, the projects do not steadily meet technical standards for monitoring, evaluation, and learning (MEL) processes. The projects prioritize short-term ecological indicators, specifically biodiversity; while lacking quality long-term social and technical indicators, though capturing a diversity of potential contributions of NbS. The study suggests that diversity in what constitutes good information and data for measuring contributions to urban adaptation demonstrates demand for flexible, commonly agreed-upon guiding principles.

Similarly, Goodwin et al. [52] screened 823 NbS initiatives globally, collected from nine secondary databases on NbS and climate adaptation actions. The research mapped 216 individual NbS interventions in 130 cities across 55 countries. The authors analyzed ten integral features of NbS grouping into three different fundamental Climate-Biodiversity-Society (CBS) challenges, including Climate challenges (which hazards are addressed and how), biodiversity challenges (how ecological aspects of NbS are supported toward urban climate resilience outcomes), and social challenges (NbS and social justice issues). Accordingly, within climate challenges, intense precipitation like flooding, landslides, and soil erosion was addressed in 81 % of interventions; increasing temperatures such as heat stress, and urban heat island effect were addressed in 59 % of interventions; drought was addressed in 26 % of interventions; and coastal hazards were addressed in 11 % of interventions. When it comes to biodiversity challenges, the study reports green and blue infrastructure approaches are more dominant, representing 56 % of entire interventions, particularly in Europe, with ecosystem-based adaptation being used frequently in most other cities. It also suggests terrestrial ecosystems, ecosystem restoration, and ecosystem protection were more common, constituting 48 %, 45 %, and 50 % of entire interventions, respectively. Lastly, within social challenges, the study demonstrates nearly 80 % of interventions received public funding, within the context of publicly implemented initiatives.

Serrano-Núñez et al. [53] evaluated hydrological response of NbS in socio-economically vulnerable tropical urban settlements, in La Guapil, a densely populated and socio-economically vulnerable urban settlement in Costa Rica, known nearly for 80 % impervious surfaces. The authors carried out intensive topographic survey utilizing a Remotely Piloted Aircraft System (RPAS) Matrice 300 RTK, equipped with a LiDAR sensor, to acquire a detailed point cloud of 95 million data points. The purpose was to establish classified point clouds, a digital terrain elevation model (DTM), and a digital surface elevation model (DSM). The research evaluated RCP8.5 climate change scenarios employing the

Clausius-Clapeyron (CC) relationship. The collected data served to calibrate and validate the Storm Water Management Model (SWMM) and the Iber model, with three simulated scenarios: (1) Status quo (current conditions), (2) Green roofs and green improvements, and (3) Detention ponds and green improvements (Iber model used). The simulations indicated scenario 2 attained the highest reduction in peak flow (53.74 %) and runoff volume (57.60 %) relative to scenario 1. Scenario 3 reduced peak flow by 28.37 % and runoff volume by 56.42 % relative to scenario 1. The study concluded that in socio-economically vulnerable urban areas like La Guapil, Costa Rica, implementing NbS, specifically green roofs and green improvements, significantly optimize stormwater management and hydrological conditions, even under climate change scenarios. The findings offer a basis for further research and the development of NbS prototype in similar regions.

In Cheltenham, UK, Torkfar and Russo [54] simulated the effects of increasing the percentage of NbS on variables such as temperature, relative humidity, and thermal comfort, in a car park chosen for its limited vegetation and potential for regeneration with NbS. Through a 3-day design workshop, two design scenarios were established integrating 30 % and 50 % NbS into the regeneration of the car park. To simulate and analyze the temperature impacts of the two design scenarios, ENVI-met version 5.0.3 software was used, with weather data from the second-highest heatwave in Cheltenham, UK, in 2017 and 2050 projections. The study reports NbS could reduce the mean radiant temperature by 6 °C to 15 °C. It points out 50 % NbS scenario led to an average decrease of 1.5 in the projected mean vote (PMV) value, demonstrating an improvement in thermal comfort. The study also underscores the comparison between the 30 % and 50 % NbS scenarios depicted the importance of strategy implementation.

Analysis of effectiveness of NbS for urban climate resilience

Nine out of the 84 articles examined the effectiveness of NbS for urban climate resilience. With this regard, considering Addis Ababa, Ethiopia, as a case study, Feyisa et al. [55] analyzed the efficiency of urban parks in mitigating urban heat island (UHI) effect. The authors measured air temperature and humidity in 60 plots within nine parks over 15 days. They used thermal bands from Landsat ETM+ satellite imagery to measure the cooling impact of 21 parks on a larger spatial scale. The researchers used statistical model, linear mixed-effects models, to analyze the relationship between vegetation characteristics and observed temperatures. During the study, the park cooling intensity (PCI) was estimated to evaluate the cooling effect of parks on their surroundings. Additionally, the park cooling distance (PCD) was measured to calculate the range within which the cooling effect could be observed. Accordingly, the study confirmed Eucalyptus species demonstrated a substantially higher cooling effect relative to other species, whereas *Stevia* and *Cupressus* showed the least impact on temperature. The maximum PCI and PCD estimated were 6.72 °C and 240 m, respectively. It was found that PCI positively associated with the Normalized Difference Vegetation Index (NDVI) and the park's area. Similarly, PCD was positively associated with shape index (SI) and area of the park, but negative relationship was observed between PCI and SI. The study concluded that the species group, canopy cover, size, and shape of the parks are key factors governing the cooling effect of urban parks in Addis Ababa.

Anjum et al. [56] analyzed the effectiveness of nature-based solutions to address climate change in Dhaka, Bangladesh. Between April and May 2023, qualitative data was collected via face-to-face in-depth interviews. A total of 45 interviews were carried out in the Gulshan and Banani regions, with a slightly equal split between male and female participants. Using a purposive sampling approach, participants were chosen based on their engagement with NbS, specifically green spaces. The interview questionnaire involved NbS, NbS strategies, social demography, climate change, ecosystem vulnerability, and socio-economic vulnerability. A qualitative approach was utilized,

alongside inductive content analysis and thematic analysis, to analyse the collected data. The results indicated NbS reduce the ecosystem, socio-economic vulnerability aspects, and climate change. It was found that rooftop agriculture and balcony gardens were regarded the most helpful and feasible NbS approaches, providing cooling effects, reduced heat stress, and better quality. The study suggested adopting NbS in urban areas enhances resilience to climate change, positively affecting communities and future efforts to maintain sustainable green space management.

To evaluate the impact of NbS on the 'Fischbeker Höfe' project in Hamburg, Germany, within the CLEVER-cities H2020 project, Scharf et al. [57] employed Greenpass system. Applicable at different scales, including city, district, or object, Greenpass, a software as a service (SaaS) tool is designed for climate-resilient urban planning and architecture. To evaluate design solutions associated with thermal comfort, energy, water, and air fluxes; standardized tools, reports, key performance scores (KPS), and key performance indicators (KPIs) used in the Greenpass system. The study intends to compare the climate resilience of the 'Fischbeker Höfe' urban development area with a conventional architecture which does not include NbS. The study confirms climate resilience analysis of 'Fischbeker Höfe' improved in four out of five KPS relative to conventional architecture. Additionally, it reports Greenpass system identified as a crucial tool for supporting climate-resilient urban design, offering a standardized and scientific basis for decision-making.

In the Medina del Campo Groundwater Body (MGWB), Spain, Martín et al. [58] analyzed the potential of NbS for conserving and enhancing water resources management without compromising agricultural productivity. A mathematical modelling, System Dynamics (SD) Modelling, was employed to mimic and understand the non-linear behavior of complex systems. To analyze the long-term effectiveness of NbS strategies under different climate scenarios, a system dynamics model (SDM) was developed, together with linked first-order differential (integral) equations as stocks and flows, describing system behavior. Additionally, participatory modelling approach was employed to co-design the SD model, combining local and scientific knowledge. Moreover, the quantitative system dynamics model was incorporated with three regional downscaled Representative Concentration Pathways (RCPs) ensembles climate scenarios. The study demonstrates the need for establishing customized and scientifically-based information about the impacts of climate change on NbS as a vital prerequisite to uphold their long-term effectiveness. It recognizes the active engagement at all societal levels as a crucial component to enhance and maintain ecosystem resilience and, hence, NbS effectiveness.

Considering climate change impacts, Baida et al. [59] analyzed the effectiveness of NbS for flood mitigation, both fluvial (riverine) and pluvial (rainfall-related) flooding, and water resources preservation in Zaio, North-East Morocco. The Representative Concentration Pathway 8.5 (RCP8.5) scenario was utilized to account for climate change impacts. To consider the expected rise in temperature due to climate change, the Intensity-Duration-Frequency (IDF) curves were modified. To simulate the impact of detention ponds on fluvial flood depths, a 2D hydrodynamic model was employed. Moreover, to quantify the impact of green infrastructure (green roofs, permeable pavements, vegetative swales) on pluvial flood discharge, the Storm Water Management Model (SWMM) was used. Based on criteria like slope, pervious areas, proximity to the river, distance from roads, and land use types, a site suitability analysis was conducted to identify optimal locations for NbS implementation. Accordingly, detention ponds reduced riverine discharge by 28.95 %, and green roofs, permeable pavements, and vegetative swales reduced pluvial water discharge by 44.7 %. In general, the study offers evidence for the effectiveness of NbS in urban flood management and water resource preservation, providing data for urban planners and policy-makers.

Rayan et al. [60] developed an indicator-based framework based on the perspectives of local stakeholders to build climate-resilient urban regions in Pakistan. Using 172 questionnaires, a comprehensive online

survey themed around urban green infrastructure (UGI), urban resilience, and climate adaptation was administered. Purposive sampling was employed to group experts as practitioners, policy-makers, academicians, and students, with snowball approach to identify specific actors. The Relative Importance Index (RII) and Interquartile Range Technique (IQR) were utilized to analyze data. Previously developed frameworks considered basis for this study. For instance, the first UGI conceptual framework developed by Rayan et al. [61] in the same year was based on Driver-Pressure-State-Impact-Response (DPSIR) framework. The study recognized 22 sustainable UGI indicators, grouped into three main categories as per their importance levels, including extremely important, important, and moderately important. The study supports the relationship between green spaces, climate resilience strategies, ecosystem functions, and human well-being in the region. It suggests the established UGI model can help evaluate the effectiveness of NbS, considering the essential indicators, as well as facilitate policy planning and decision-making processes for resilient and sustainable urban environment.

Similarly, Rayan et al. [62] analyzed a UGI indicator-based framework model, based on the stakeholders involvement, to improve climate resilience in Pakistan’s Khyber Pakhtunkhwa (KP) province. Unlike Rayan et al. [61], this study consulted local stakeholders, including local communities and experts in KP. However similar procedures of RII and IQR techniques were followed to analyze data, and classify sustainable UGI indicators according to their importance. The findings reveal ecological and economic dimensions were rated as important, RII = 0.835 and RII = 0.807, respectively, whereas socio-cultural dimensions were moderately important, RII = 0.795. The individual UGI indicators were rated as important (RII ≥ 0.77) as a set of urban green space elements, hence reducing rainwater runoff, RII = 0.94; enhancement of mental and physical health, RII = 0.90; and minimizing the risk of flood disasters, RII = 0.96. overall, the study suggests the need for an inclusive perspective while establishing urban green space infrastructure to ensure effectiveness.

Chan et al. [63] utilized a two-tiered process to establish indicators for sustainable urban park management in Hong Kong, engaging 20 park managers, nine local scholars, and 743 park users. The study investigated the level of importance of each indicator and ranked all set. Based on the user-perceived level of importance, each indicator demonstrates that users pay due attention to consider the environmental quality of parks to be essential management aspects.

In Addis Ababa, Ethiopia, Eshetu et al. [64] conducted a study to analyze urban green space planning, policy implementation, and challenges. To collect data, key informant interviews were conducted with administrators and experts from relevant government organizations. Additionally, the study utilized field observations, focus group discussions, and satellite images to collect data. Stakeholder consultations were used to analyze stakeholder and institutional arrangement mapping. Data sourced from focus group discussions and key informants were triangulated with documents and observations for validation.

Furthermore, government document review was carried out to analyze their impact on green space planning, implementation, and effectiveness. The study suggests existing policies require legislative regulations and implementation frameworks for tangible action plans. It reports directives and regulations are not clearly drafted by responsible bodies, therefore, law enforcement hinders green space development and effectiveness in Addis Ababa.

Overall, NbS can enhance urban climate resilience, but their success depends on context-specific design, stakeholder involvement, robust policy frameworks, and ongoing evaluation. The core ideas of ICE within this qualitative analysis based on the specific review questions (RQs) is shown in Fig. 8.

Discussion

Factors to consider during NbS implementation

Nature-based solutions implementation needs careful consideration of stakeholder engagement, policy integration, and institutional support. These elements are vital for the successful adoption and sustainability of NbS projects. Collaborative planning is an essential component of stakeholder engagement. For instance, effective NbS implementation takes advantage from participatory approaches that engage multiple stakeholders, including local communities, decision-makers, and experts. Such a collaboration helps co-designing and co-implementing solutions, ensuring they are effective and well-received [65–67].

Citizen participation is also another component. Deeper forms of citizen involvement enhance social outcomes, including environmental stewardship and inclusiveness, but tokenistic participation usually limits these benefits [68]. Stakeholder mapping is also essential to identify and involve the right stakeholders at each stage of the project to reduce bottlenecks and enhance planning efficiency [69].

Successful NbS initiatives often need integration into existing policy frameworks, including aligning with urban planning strategies and ensuring that NbS are part of comprehensive policy agendas such as climate adaptation and disaster risk reduction [65,66]. Overall, effective policy integration includes understanding local situations and ensuring that NbS are adaptable to these situations, but this needs a vigorous policy framework that underpins the long-term sustainability of NbS [70].

Regarding institutional support, multiple institutional scales and sectors enhance the governance of NbS, making them more resilient and adaptable to various challenges [65,67]. Sufficient financial incentives and institutional support, including secured funding and ensured institutional commitment to NbS projects are also crucial to facilitate the implementation and monitoring of NbS [71].

Contributions of NbS to urban climate mitigation and adaptation

Nature-based solutions significantly contribute to climate change

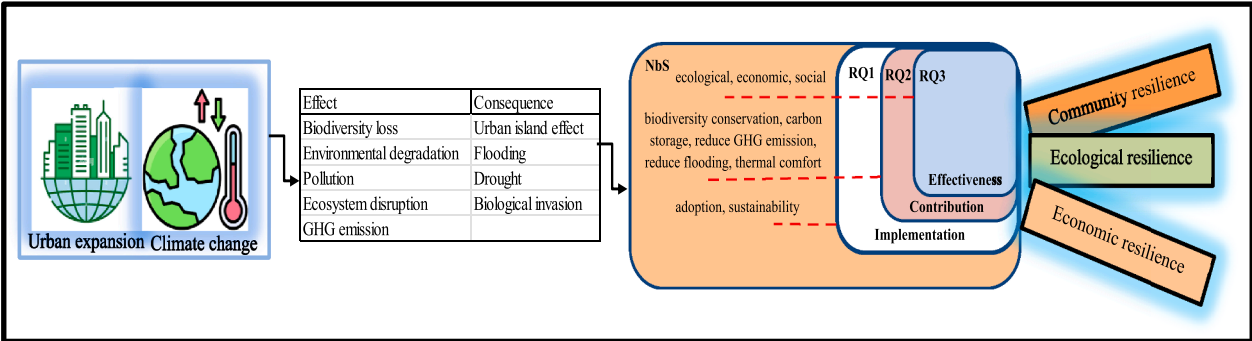


Fig. 8. A diagram representing core ideas of ICE within qualitative analysis based on the specific review questions (RQs).

mitigation and adaptation in urban environments. They are increasingly prominent in global climate change policy, with 66 % of Paris Agreement signatories indicating interventions to work with urban ecosystems to tackle climate change impacts [72]. Nature-based solutions involve conserving and restoring natural ecosystems to address societal challenges while offering benefits for human welfare and biodiversity [23]. Green spaces and urban forests store carbon, contributing to reduce greenhouse gas (GHG) emissions and mitigate climate change [73]. Moreover, green walls and roofs reduce the energy required for heating and cooling buildings, thereby decreasing emissions from energy consumption [74,75].

Urban green spaces and trees reduce ambient temperatures, addressing the urban heat island effect and optimizing thermal comfort for inhabitants [76]. With this regard, Torkfar and Russo [77] report NbS incorporation decrease mean radiant temperature by 6 to 15 degrees and optimize thermal comfort, demonstrating its potential climate adaptation benefits. It has also been reported that NbS are the most effective in high temperature and air pollution cities such as Genova, with a 12 % improvement in nitrogen dioxide concentration [78]. Similarly, in Izmir, Turkey, NbS like large deciduous trees improve thermal comfort and decrease urban temperature with potential of up to 2.5 °C [79].

Raingardens, wetlands, and permeable surfaces support management of stormwater runoff, decreasing the risk of urban flooding and waterlogging [80]. Furthermore, marshes, mangroves, and other coastal ecosystems safeguard against sea-level rise and storms, protecting urban

environments from coastal erosion and flooding [81]. Study reports that in the coastal city of Aveiro, Portugal, green roofs save 32 % of annual flood damages to buildings and infrastructures, under current and future climate conditions [82].

Global reports such as IPCC Assessment Reports have affected academic research on climate impact mitigation and adaptation in urban environments, however, more combined mitigation and adaptation policies and strategies are required for increased resilience [83]. A similar trend is observed within the case of NbS. In urban planning, NbS support climate change mitigation and adaptation, but more research is required to integrate biophysical and economic assessments to determine the avoided costs and benefits of their implementation [84].

Indicators for evaluating NbS effectiveness

Evaluating the effectiveness of NbS encompasses measuring their capacity to address ecological, economic, and social issues while offering co-benefits. To measure these outcomes, different frameworks and indicators have been developed so far, as illustrated in Fig. 9, based on the results of various literature.

Ecological indicators. Ecological indicators involve metrics for stormwater management, biodiversity enhancement, and climate change adaptation. For example, NbS reduce urban heat islands, enhance soil quality, and optimize water retention [85–87]. **Economic indicators.** Economic efficiency and cost-effectiveness are essential for comparing NbS with conventional grey infrastructure. This could be

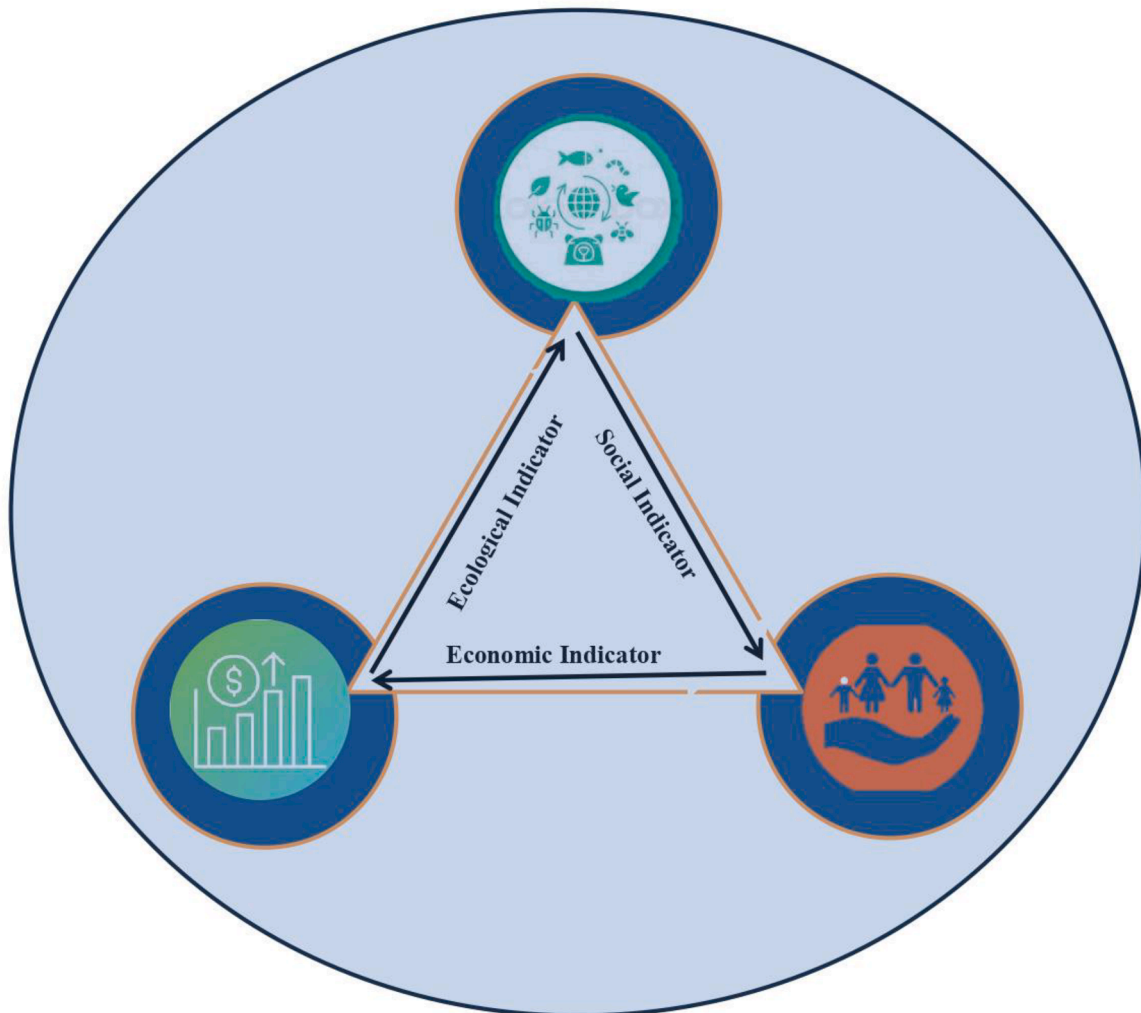


Fig. 9. Triangular indicators for evaluating effectiveness of NbS for urban climate resilience.

measuring the economic benefits of ecosystem services offered by specific NbS [70,88]. **Social indicators.** Social indicators involve human welfare, recreational values, and community engagement. In this regard, stakeholder participation and the socio-cultural benefits of NbS are vital for their recognition and success [89,90].

In some cases, performance and monitoring and process-based indicators are also considered to evaluate the effectiveness of NbS. **Performance and monitoring.** The application of remote sensing and ground-based measurements assist in monitoring the performance of NbS against natural hazards like floods and droughts. These approaches offer data for assessing the effectiveness of NbS over time [88]. **Process-based indicators.** Process-based indicators involve the expertise and roles of engaged actors, including political support, and the adaptability of NbS to local situations [89].

Review limitations

The systematic review is limited by its emphasis on English Language original research, possibly overlooking substantial contributions published in other languages, particularly as NbS research is globally diverse. The reliance on sources having agreements with our institution and freely accessible, disregarding databases such as Web of Science, further limited the scope of the review. Moreover, the review's search procedure, that needed the explicit use of "Nature-based solutions" or "NbS" in article titles, potentially excluded relevant research that discussed NbS through local or regional names. These limitations thus collectively decreased the number of articles included in the final analysis, impairing the comprehensiveness of the results.

Research gaps and future directions

The analysis demonstrates critical research gaps in NbS implementation, contribution and effectiveness (ICE) in addressing urban climate resilience, mainly stemming from methodological inconsistencies and inadequate data. A complete reliance on secondary data and modelling, rather than primary field data, impairs the depth and accuracy of current research. For instance, of the 26 qualitative sample publications selected for this systematic review, nearly 54 % employed only secondary data sources (Appendix A). Additionally, eight publications lacked clear and specified data analysis techniques (Appendix A). These hinder the exploration of tradeoffs, synergies, and the overall status of ICE, as well as their connection to urban climate resilience. Moreover, the absence of a standardized methodology throughout empirical studies using similar NbS types poses challenges in synthesizing and comparing research findings.

A wider research gap observed in understanding the complex functions of ICE of NbS in tackling urban climate resilience. Empirical studies often lack depth, failing to recognize the underlying mechanisms of these functions. Addressing this gap needs studies that consider ICE on NbS potential, a detailed understanding of dynamic urban ecosystems, and the use of appropriate data, models and software. Future research should focus on optimizing NbS to maximize synergies across ecological and social pathways, moving beyond a one-size-fits-all approach [21]. There is a need for a transdisciplinary perspective that links ecological sciences, landscape architecture, and social sciences to co-create NbS using participatory approaches [91]. This approach can help bridge the gap between different interpretations of urban nature and enhance the practical implementation of NbS. Additionally, future research and policy agendas should emphasize producing stronger evidence for their effectiveness, adapting governance strategies, and ensuring socio-environmental equity to maximize the benefits of NbS [26]. While enabling urban planning practices to adjust and build local capacity, pilot projects help address the urgency of implementation [23]. Furthermore, integrating local practices into broader climate adaptation

strategies optimizes the spatial and ecological importance of small-scale NbS [92].

Future research should also prioritize data collection and utilize rigorous methodologies for precise assessment and monitoring, supporting decision-making and policy development. Moreover, there is a need to examine unexplored aspects of NbS, specifically ICE within the context of urban climate resilience to develop reliable research methods. A geographical bias towards the northern hemisphere, particularly Europe and USA, demands expanding research to underrepresented NbS. This demonstrated through the fact that 33 publications from the total 84 articles were originated from Europe and USA (Appendix A). Towards this end, a deeper understanding of NbS strategies and the development of effective resource management options are mandatory.

Conclusion

With the urgent need to enhance urban climate resilience, research on ICE of NbS is critical. This review systematically evaluated 84 publications, employing primarily qualitative approach, to offer an overview of contemporary NbS literature. The review categorized based on objectives and outcomes, considering three key review questions. This systematic review intended to demonstrate potential pathways for future research, specifically focusing on the value of flexible qualitative methods to complement quantitative studies, by identifying cohesions and differences. Collectively, thus, the review highlights that though NbS hold substantial promise for optimizing urban climate resilience, their successful implementation is contingent upon addressing a complex relationship between factors like data-driven planning, stakeholder awareness and engagement, resource availability, institutional framework, and context-specific considerations. Moreover, it demonstrates the significance of integrating ecological, economic, and social dimensions, tailoring interventions to local needs, and utilizing rigorous evaluation methodologies to ensure the effectiveness and long-term contribution of NbS in fostering resilient urban environments to the climate change impacts. Though the scope of this review was constrained by various factors, it identified significant research gaps, including reliance on secondary data and sources, methodological inconsistencies, lack of standardized approaches, and inadequate understanding of the complex functions of NbS in urban climate resilience. Hence, future research should prioritize primary data, robust methodologies, transdisciplinary collaboration, and a broader geographical focus to promote the effectiveness and successful implementation of NbS.

CRediT authorship contribution statement

Gemechis B Mosisa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bohe Bedadi:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Gemedo Dalle:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Nega Tassie:** Writing – review & editing, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

NBS Impacts and Implications

- A deeper understanding of the major socio-economic and governance issues, as well as enabling factors, will equip policymakers and practitioners with the knowledge to design and implement more effective and context-specific NbS in urban areas.
- Cities can strategically integrate these solutions into their climate adaptation and mitigation plans, by understanding the extent and mechanisms through which specific NbS contribute to addressing climate-related challenges, leading to more resilient urban environments better prepared to withstand climate impacts.
- The development of robust methods for measuring and monitoring the long-term effectiveness of NbS, including their ecological, social, and economic impacts, will provide vital data for evidence-based decision-making. This will allow for better evaluation of investments in NbS and the optimization of their design and implementation for maximum benefit.

Appendix A. Analysis of sample existing literature

Author/Year	Geographic Area	Criteria	Data / collection	Data analysis
Velayo et al. (2024)	Philippines	Implementation	Social surveys	Not specified
Sari et al. (2023)	Italy	Implementation	Social acceptance framework	Not specified
Voskamp et al. (2021)	Europe	Implementation	Expert interviews	Descriptive statistics
Young et al. (2019)	Brazil	Implementation	Surveys	Content analysis
Boateng et al. (2023)	Ghana	Implementation	Social Surveys	Thematic analysis
Glytsos et al. (2025)	Greece	Implementation	Literature values	ENVI-met software
Pancewicz et al. (2023)	Poland	Implementation	Project & policy documents	Not specified
Dubo et al. (2022)	Alpine Convention	Implementation	Different databases	Spatial analysis
Simperler et al. (2020)	Germany	Implementation	Citizen science data	Spatial analysis
Bernello et al. (2022)	Italy	Implementation	Online surveys	Logistic regression
Vojvodíková et al. (2022)	Poland	Implementation	Social surveys	Not specified
Beceiro et al. (2020)	Europe/Canada	Contribution	Resilience Assessment Framework	Not specified
Conti et al. (2021)	Italy	Contribution	Qualitative case study	Resilience thinking
Goodwin et al. (2024)	Global	Contribution	Literature & interviews	Mixed methods
Goodwin et al. (2023)	Global	Contribution	Different databases	Not specified
Serrano-Núñez et al. (2024)	Costa Rica	Contribution	Topographic survey	Not specified
Torkfar & Russo (2023)	UK	Contribution	Design workshop	ENVI-met software
Feyisa et al. (2014)	Ethiopia	Effectiveness	Geospatial data	Linear mixed-effects
Anjum et al. (2024)	Bangladesh	Effectiveness	Interviews	Content & thematic analysis
Scharf et al. (2021)	Germany	Effectiveness	Project data	Greenpass software
Gómez Martín et al. (2021)	Spain	Effectiveness	Participatory SD model	Differential equations
El Baida et al. (2024)	Morocco	Effectiveness	RCP8.5 scenarios	Different models
Rayan et al. (2021)	Pakistan	Effectiveness	Online surveys	RII & IQR
Rayan et al. (2022)	Pakistan	Effectiveness	Stakeholder surveys	RII & IQR
Chan et al. (2018)	Hong Kong	Effectiveness	User surveys	Not specified
Eshetu et al. (2021)	Ethiopia	Effectiveness	Surveys	Triangulation

Data availability

Data will be made available on request.

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