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How nature-based solutions can enhance urban resilience to flooding and climate change and provide other co-benefits: A systematic review and taxonomy

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ABSTRACT

Planning clean, livable, and resilient cities is challenging. This becomes even more complex when considering the rapid population growth and urban development. The development of nature-based solutions (NbS) is acknowledged as a viable strategy to address this issue. It has multiple human and environmental health benefits under both normal and extreme climatic scenarios. This study aimed to examine how different conditions and factors are linked to the development of NbS for urban climate change adaptation, with a specific focus on stormwater and flooding management. Through a systematic literature review, this study proposes a taxonomy of NbS to better understand the processes and hierarchies involved in developing NbS. The analysis covered multiple factors related to geographical focus and scale, sector, climatic conditions, adaptation and mitigation measures, ecosystem services, and co-benefits. These factors were linked to ten classified NbS approaches and 29 specific NbS interventions. An analysis of 582 empirical studies showed that Sustainable Urban Drainage Systems (SUDS) are the most dominant approaches of NbS for adaptation, followed by Low-Impact Development (LID), Green Infrastructure (GI), Sponge City (SC), and Blue-Green Infrastructure (BGI). Among the different interventions, green roofs play a significant role in providing multifunctional ecosystem services and adaptation benefits such as stormwater and climate regulation. Policymakers and developers aiming to expand the implementation of NbS can consider the taxonomy proposed in this study to choose the right types of NbS and obtain maximum co-benefits.

1. Introduction

Cities play a significant role in driving climate change and are highly vulnerable to its impacts (Bona et al., 2023; Ghaemi & Smith, 2020). They must deal with numerous risks such as heatwaves, floods, water infrastructure disruptions, air pollution, health problems, and environmental concerns (Hritonenko & Yatsenko, 2022). Therefore, urban policy plays a crucial role in adapting to climate change (Aboagye &

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Sharifi, 2023, 2024; Mariano & Marino, 2022). Climate adaptation is an adjustment process to the actual or expected climate and its effects on reducing climate risks and vulnerability. Adaptation involves interventions in biological, social, and built systems to cope with climate change (IPCC, 2022b). Adaptation options can immediately and gradually affect social, economic, political, and environmental systems. Although technologies, science, and policy innovations help with adaptation, they often involve costly solutions (IPCC, 2022b; Owen, 2020). On the other hand, mitigation refers to measures that reduce Greenhouse Gas (GHG) sources such as carbon dioxide (CO_2) and methane (CH_4) and/or improve their sinks (Fawzy et al., 2020; IPCC, 2022a).

Urban nature-based solutions (NbS) have the potential for adaptation and mitigation; however, it is not entirely clear how NbS can drive transformative changes in cities worldwide (Goodwin et al., 2023). Although NbS has gained recognition as a sustainable approach, it remains a topic of debate in many cities owing to the uncertainties surrounding its implementation. Consequently, they have not received sufficient attention. The scientific community can help address these concerns by examining the benefits, limitations, and effectiveness of NbS in reducing the risks and stressors induced by climate change and adapting to their impacts, particularly in stormwater (Holden et al., 2022; Seddon, 2022). To promote NbS effectively and sustainably, their long-term operation, a variety of ecosystems, biodiversity benefits, and local knowledge should be engaged in design, research, and practice (Seddon et al., 2021; Wu & Hong, 2023). In this regard, seven stages, including target identification, selecting NbS type, process design, implementing NbS, stakeholder engagement and co-benefit consideration, upscaling NbS, monitoring, and co-benefit evaluation, have been proposed to implement NbS, assess their co-benefits, and discuss their dynamic interactions (Raymond et al., 2017). Selecting a specific type of NbS plays an essential role in this process. Therefore, recent publications have discussed different types of NbS and their classification. For instance, Nehren et al. (2023) proposed a typology of NbS that could be integrated with disaster risk reduction (DRR) and climate change adaptation measures .

However, the combined impacts of climate change and rapid urbanization have exacerbated stormwater management challenges, mainly because of the disruption of the natural water cycle (Fletcher et al., 2015; McGrane, 2016; Sun et al., 2021). Coping with urban water challenges, including stormwater management, green infrastructure (GI), and its integration with urban infrastructure, has been recognized by city planners, policymakers, and researchers for a relatively long time (Grabowski et al., 2022; O'Donnell et al., 2017). GI can be categorized into greenspace planning, urban ecology, and water/stormwater management, which intersect with the ecosystem services concept, engineered facility types, and implicit definitions (Matsler et al., 2021; Nazmul Haque & Sharifi, 2024). The conceptualization and operationalization of GI requires strategic planning aligned with several principles, such as connectivity, multifunctionality, applicability, integration, diversity, multiscale, governance, and continuity (Grădinaru & Hersperger, 2019; Hölscher et al., 2024; Monteiro et al., 2020).

Furthermore, in response to rapid urbanization and land use change, NbS implementation necessitates research to assess climate-land use change impacts, simulate ecological restoration programs, and identify restoration thresholds (Yang et al., 2022). Ecosystem-service approaches and NbS can be integrated to strengthen urban climate resilience and sustainable development (Batalini de Macedo et al., 2022; Ma and Jiang, 2023; Sharifi, 2023). Today, there is a strong and positive outlook on the value and services provided by nature. In particular, lessons learned during the COVID-19 pandemic regarding the role of nature in managing widespread diseases highlight its importance and effectiveness (Everard et al., 2020). Based on previous research, GI has a well-recognized history in urban planning (Grabowski et al., 2022; Wang et al., 2024). However, there are still some issues that need to be addressed. For instance, there is a disparate and unbalanced understanding of how NbS can simultaneously and comprehensively address climate change impacts, biodiversity loss, economic and social development, and enhance human health and food and water security (Dunlop et al., 2024; Goodwin et al., 2023; Lamb et al., 2019). In addition, it is still unclear how NbS should be implemented and how they affect individual accessibility and co-benefits (Petzold & Mose, 2023). Therefore, NbS must be systematically studied before being incorporated into decision-making, planning, and practice. A critical factor in scaling up NbS is revealing the potential of different NbS types to deliver benefits (Cortinovis et al., 2022). In this regard, a taxonomy can help clarify terms and functions, and provide more objective design and implementation. A taxonomy that connects NbS types to climate adaptation can reduce the complexity of selecting suitable types of NbS for short- and long-term resilience. It can also shed light on the interactions between various types of NbS, their geographical distribution, desired scales, responsible sectors, ecosystem services provided, and co-benefits. Nevertheless, this study aims to address the following questions: What are the holistic values and benefits of urban NbS, as well as who benefits from them? Are various NbS concepts differentiated in different geographical contexts? Are practices (interventions) associated with the scale in which they are studied and implemented? How can NbS be associated with ecosystem services, adaptation potential, and other co-benefits and how can they be linked to mitigation? Therefore, the main objective of this study is to propose a taxonomy for NbS and identify and examine the potential contribution of various types of urban NbS to climate change adaptation, particularly stormwater regulation. To the best of our knowledge, no review study has been conducted from this perspective (taxonomy). The findings of this study clarify and distinguish the incorporation of NbS into urban design, planning, and policymaking.

Section 2 presents the definition of NbS and different concepts for stormwater management. Section 3 provides a detailed description of the materials and methods used in this paper. In Section 4, the results of the analysis are presented. In Section 5, three distinct aspects of the key findings are discussed and interpreted. The limitations and recommendations for future research are discussed in this section. Finally, Section 6 concludes the study and provides policy implications.

2. Nature-based water and stormwater management concepts

Many cities worldwide employ NbS to address climate change impacts, biodiversity loss, urban heat island (UHI) effects, air quality, and health and well-being issues (Ascenso et al., 2021; Mabon, 2023; Oukawa et al., 2024). According to the Global Standard for Nature-based Solutions (IUCN, 2020; Sowińska-Świerkosz & García, 2022), NbS refers to actions that:

- are designed to integrate multiple ecosystem services and functions to address societal challenges.
- are characterized by cost-effectiveness, inclusivity, transparency, and empowerment of governance processes. They can also effectively manage conflicting objectives equitably.
- are sustainable and align with sectoral, national, and other policy frameworks that can be managed adaptively.

Urban areas are becoming increasingly vulnerable to the impacts of climate change, particularly extreme weather events. These risks pose significant challenges for cities, both now and in the future. This has implications for human health and well-being (both physiological and psychological) (Kolokotsa et al., 2020). NbS are useful for addressing challenges and providing benefits, such as cooling city areas, flood mitigation, capturing stormwater, reducing pollution, improving human well-being and biodiversity, and circularity in cities (Oral et al., 2020; Razzaghi Asl, 2023). NbS are built upon traditional strategies for conserving and managing biodiversity, and they integrate scientific research, policy development, and practical implementation. They evolve diverse and well-managed ecosystems that benefit biodiversity

(Dignum et al., 2020; Eggermont et al., 2015). Despite the different risks and uncertainties associated with climate change, NbS integrate natural and semi-natural ecosystems into urban systems and offers benefits, such as pollutant filtering and oxygen production (Bayulken et al., 2021). Furthermore, NbS can protect communities and enhance their livelihoods (UNEP, 2019). To improve water provisioning and other ecosystem services, for instance, NbS relies on reforestation, wetland restoration (Yimer et al., 2024), and rainwater harvesting, which are more environmentally friendly than traditional methods such as dams and water diversion canals. NbS are expected to contribute to achieving global sustainable development goals (Huang et al., 2020; Lafortezza & Sanesi, 2019). NbS is a broad concept that dominates other concepts such as GI (Qiu et al., 2021).

Regarding water and stormwater management, NbS can be categorized into ten concepts that mimic natural processes. They overlap and could be similar, complementary, and different in their purpose, dominance, and perspectives.

- A sustainable urban drainage system (SUDS) is an idea that assumes the incorporation of natural drainage systems in urban infrastructure, and drainage systems are more sustainable. The main objective is to control the quantity and quality of urban surface water and its enhance resilience (Guptha et al., 2022; Viavattene & Ellis, 2013).
- Green infrastructure (GI) offers alternative solutions for stormwater management. It refers to tools, measures, greenspace networks, and/or systems constructed in conjunction with water bodies and aquatic systems (Caparrós-Martínez et al., 2020; Ramyar et al., 2020).
- Low-impact development (LID); are a set of measures aimed at mitigating the effects of impervious surfaces on stormwater runoff in urban areas. These measures focus on creating conditions that resemble those found in natural environments before development and promote water storage, infiltration, and evapotranspiration (Palla & Gnecco, 2015; Pour et al., 2020).
- Sponge city (SC) was originally launched in China in 2014 in 120 cities, at national and provincial scales, with the aim of enhancing the capacity of urban ecosystems to manage urban water challenges under the impact of climate change. Decentralized nature-based structures can effectively enhance the on-site retention and groundwater infiltration. They have proven beneficial in reducing runoff and mitigating pollution overflow. Furthermore, it enables water storage and harvesting, while simultaneously enhancing environmental features (Ma & Jiang, 2023; Ma et al., 2020).
- Blue-green infrastructure (BGI) is defined as interconnected green and blue measures such as natural, semi-natural, and constructed ecosystems such as water bodies with hydrological functions to deliver water resources, flood management services, and environmental and health benefits. BGI emphasizes blue infrastructure, specifically stormwater management and flood risk reduction (O'Donnell et al., 2021; Voskamp & Van de Ven, 2015).
- Green stormwater infrastructure (GSI) explicitly refers to strategies for urban stormwater mitigation and climate change adaptation. The definition of GSI varies across academic literature; however, it can refer to physical characteristics that include a combination of ecological and technological elements that are strategically designed to regulate stormwater. GSI approaches, such as detention ponds, can be centralized or decentralized, including smaller GSI features, such as bioswales, bioretention basins, and infiltration trenches (McPhillips & Matsler, 2018; McPhillips et al., 2021).
- Urban greenery (UG) refers to the existence and amount of greenery such as trees, plants, gardens, parks, and other open spaces. It offers various advantages, including urban heat island effect mitigation, air pollution reduction, stormwater and flood risk management, social and recreational enhancement, and mental health and well-being improvements (Andersson-Sköld et al., 2015; Wang et al., 2019).
- Blue-green-grey infrastructure (BGGI) is a complementary integration of green, blue, and grey infrastructures that can enhance sustainability and urban resilience. It is a hybrid concept that considers optimizing synergies, co-benefits, and cost-effectiveness owing to the complexity and decentralization of interventions that are applied (Alves et al., 2019; Wang et al., 2022).
- Best management practices (BMPs): Implementation of BMPs is essential for effectively treating stormwater runoff. These practices encompass a range of strategies, including large-scale approaches, such as constructed wetlands and ponds that are positioned at drainage area outlets to manage stormwater runoff. Additionally, there are smaller-scale initiatives like bioretention systems and green roofs that are dispersed throughout the site to address pollution at its source (Liu et al., 2017; Loperfido et al., 2014).
- Water sensitive urban design (WSUD); is an approach that integrates urban water cycle planning and management, and design. Its main objective is to prioritize water in urban design by incorporating it with different engineering and environmental sciences related to water services, while also safeguarding aquatic environments in cities. This approach treats urban surface runoff as a valuable resource, rather than an issue (Ahammed, 2017; Ashley et al., 2013).

Fig. 1 illustrates the primary concepts of NbS and their associated concepts. In this review, all relevant and similar concepts are examined through a systematic study, and their relevant interventions and potential contributions to stormwater management and other co-benefits are discussed. All of these concepts may involve interventions such as bioretention cells, permeable pavements, rainwater harvesting systems, green roofs, detention, and retention ponds, which are explored in detail in Section 4. This review was conducted based on existing research on NbS and empirical studies that introduced, designed, modeled, implemented, and discussed the benefits of NbS and their conceptualization. Interventions such as porous pavements and rain barrels are considered helpful in protecting natural ecosystems, bringing nature to people's lives, and delivering various planetary benefits. For instance, rain barrels can facilitate the utilization of rainwater harvested from rooftops. They can even be optimal in terms of flood resilience and cost-effectiveness, among other types of interventions, such as green roofs in some areas of Brazil (McClymont et al., 2020). In addition, it can be seen that engineered vegetation measures such as porous pavements (Ferrans et al., 2022; Roseboro et al., 2021) are considered under at least one of the NbS concepts (SUDS, GI, etc.) that are categorized in the current study. In addition, we present the definition of all interventions in the Table S1 in the supplementary material. Although some types of pavements, such as porous pavements and permeable and impervious pavements, are quite similar, they can be varied based on their design for different scales, construction materials, functionality, and optimization.

3. Materials and methods

3.1. Data collection and selection

This systematic review focuses on studies that address climate change adaptation, particularly stormwater and flooding management, using nature-based solutions (NbS) and their co-benefits. We used the "Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA)" 2020 statement protocol (Page et al., 2021) for literature identification, screening, and selection (Fig. 2). For this purpose, the study started with a comprehensive search conducted on October 28, 2022, including 42 keywords in two of the largest and most broadly used scientific publication databases, Web of Science (WoS) and Scopus. The search was performed within the article title, abstract, and keywords through a query string, using terms related to climate change, adaptation, stormwater, and NbS. A summarized version of the string is presented here: (climate change OR global warming) AND ("adapt" OR "resilience" OR "response" OR "coping" OR "cope") AND ("flood" OR "stormwater") AND ("nature-based solutions" OR "bioswale" OR "green

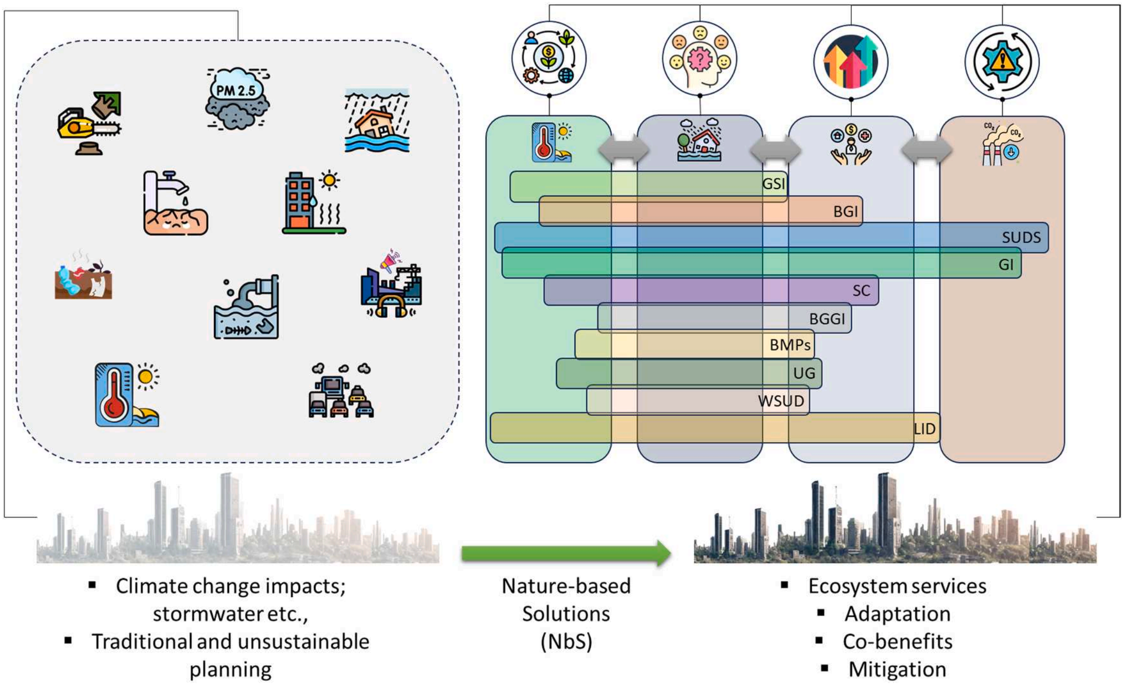

Fig. 1. The commonly recognized concepts of NbS associated with stormwater management as one of the primary objectives for adaptation to climate change. (The icons are freely available at https://www.flaticon.com/).

roof" OR "rainwater harvesting" OR "green infrastructure" OR "permeable pavement" OR "rain garden" OR "sponge city" OR "green walls" OR "green facades" OR "forestry" OR "trees" OR "parks" OR "cemeteries" OR "gardens" OR "SUDS" OR "green retrofit" OR "green bicycle lanes" AND (urban OR city OR cities OR neighborhood). The search was limited to original peer-reviewed research articles written in English. A detailed search string is available in the Online Supplementary Appendix (please click the link at the bottom of the PDF file).

Based on the initial search, 1222 WoS and 2439 Scopus documents were identified. We checked their titles, and 832 articles were selected for second-stage screening and eligibility evaluation. Review papers and duplicates were excluded from the analysis. This was done to focus on original research and to prevent potential bias by previous interpretations and classifications in previous review articles. Finally, 582 studies were considered for the content analysis.

3.2. Deductive content analysis

Deductive content analysis (DCA) uses predefined categories or concepts derived from existing theories or frameworks to analyze qualitative data following data collection, analysis, result reporting, and interpretation procedures (Moldavska & Welo, 2017). In this study, we employed DCA to analyze the content of the selected papers and reveal the underlying themes and connections. The DCA procedure followed in the current systematic review is depicted in Fig. 3 and was adapted from Cho and Lee (2014). Document collection and selection are described in the previous section (Section 3.1, Fig. 1). The specific steps are as follows. Step 1: The unit of analysis is equal to the selected papers in the content analysis. Step 2: Predetermined categories, including ten NbS concepts, are also explained in Section 2 prior to analysis. We developed an information extraction sheet in Microsoft Excel, which served as the basis for systematically categorizing qualitative data. A set of criteria was selected to extract the data and identify patterns, themes, and hierarchies. The extracted data related to geographic distribution and climate classification were input into ArcGIS software to map them globally. Step 3: In addition to these, basic information of the selected papers, including year of publication and journals, provides details on the trend and an overview of current state-of-the-art NbS studies. Other main categories were utilized to improve our understanding of the connections and patterns of urban NbS. Step 4: The derived categories and their subcategories are interpretively analyzed and synthesized to create connectedness between the categories and develop the taxonomy. Step 5: Conclusions are drawn by interpreting the proposed taxonomy. It should be noted that we ensured that all relevant aspects of the data were explored and considered in our analysis. Content analysis was conducted in three rounds. In the first round, the lead author checked all papers and extracted the necessary data. Simultaneously, the papers were also divided among the co-authors to complete the extraction sheet. In the second round, the lead author compared the extraction sheets to detect inconsistencies. Finally, in the third round, discussions were conducted among the authors to reach a consensus on cases of inconsistencies.

Despite the subjective nature of our content analysis approach, we believe that it has helped minimize inaccuracies. The coding and analysis criteria are listed in Table 1.

The attributes of these criteria are discussed in Sections (Sections 4 and 5).

4. Results

4.1. Overview of the literature

Our analysis showed that most papers have been published since 2012. The trends over the last decade are shown in Fig. 4. From 2012–2022, the number of publications has increased by more than ten times. The journals with the most articles on this topic are Water (9%), Sustainability (6%), Journal of Hydrology (6%), Science of the Total Environment (4%), Journal of Environmental Management (4%), Urban Forestry and Urban Greening (3%), Landscape and Urban Planning (2%), Water Science and Technology (2%), Urban Water Journal (2%), and Hydrological Processes (2%). In Fig. 5, the focus of the reviewed papers is presented based on the main concepts of NbS (explained in Section 2) and the types of interventions extracted in the previous section. These are linked to each other by their source counts. Table S1 of

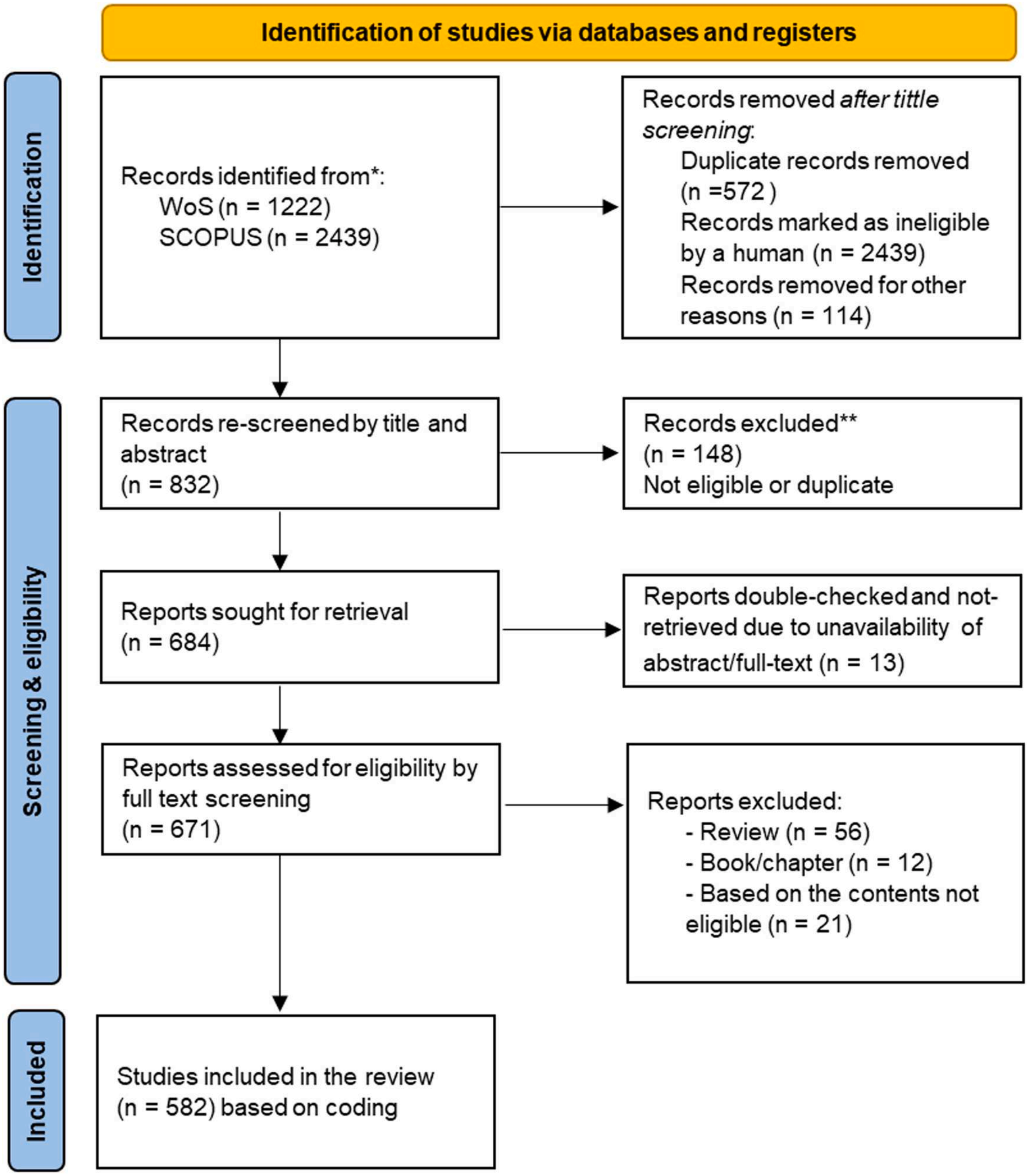

Fig. 2. PRISMA protocol for literature search and selection.

the Online Supplementary material presents specific NbS interventions and their definitions.

4.2. Taxonomy of NbS

We propose a taxonomy represented by the Sankey diagram in Fig. 6. The taxonomy was developed by combining the connections between the different criteria described in Section 3.2. Each link or flow represents a likely scenario between an attribute and target (another attribute). This shows that in different regions such as Asia (on the left), multiple objectives (on the right) can be achieved through different types of NbS interventions at different scales and climate conditions (in the middle). The objectives include adaptation, mitigation, ecosystem services, and other co-benefits, which are discussed in the following sections. It is suggested that each region can adopt its own type of NbS to contribute to adaptation, particularly to stormwater management. It was revealed that Europe, Asia, and North America were pioneers in research and practice in the field of NbS. The empirical studies analyzed were mainly conducted under temperate climate conditions, followed by cold, dry, multiple, and tropical climate conditions. As shown in Fig. 6, the regulatory services provided by NbS can be associated with several positive side effects (co-benefits) related to mitigation. We can assume that each NbS intervention provides a primary adaptation contribution (e.g., stormwater regulation and sanitation) and some indirect measures (e.g., temperature regulation). In other words, this can lead to indirect co-benefits for mitigation. However, the degree of synergistic interaction between measures to maximize co-benefits is a topic that has been partially discussed. This taxonomy provides an insightful overview of how various NbS approaches/interventions have been incorporated into scholarly work over the last decade. Each connection can offer insights into creating a scenario for NbS integration and the development of hybrid systems. This can better handle the challenges posed by a rapidly changing environmental landscape by building on the foundation established in the previous section. We introduce the different parts of

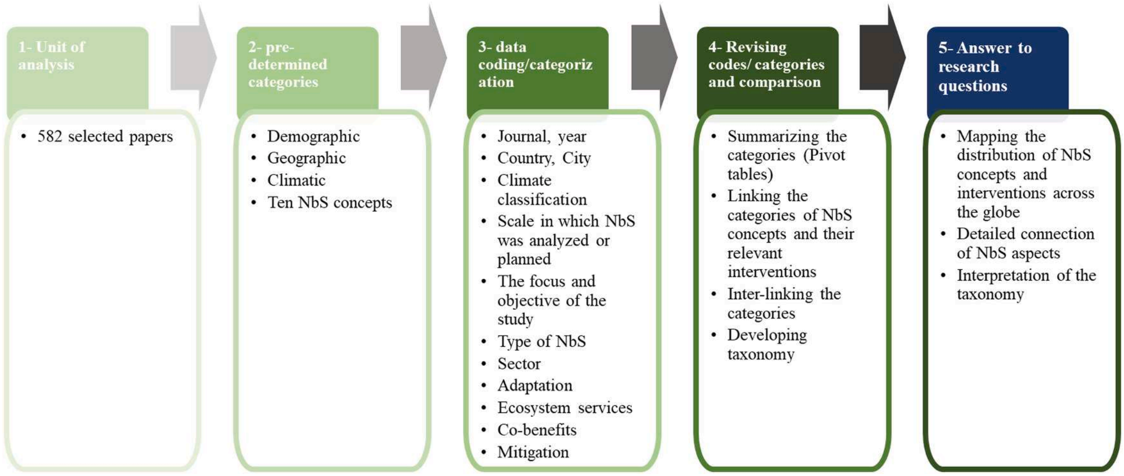

Fig. 3. Procedure of the DCA to address the research questions and propose a taxonomy.

Table 1
Criteria categories for evaluating the content of the literature and extracting data.

No.	Criteria	Description
1	Specific geographic area	The area on which the paper was focused and done (in some cases was extracted by full-text reading because it was not mentioned in the abstract).
2	Specific type of NbS	We categorized the concepts of NbS based on the (Section 2), and further, they are linked to specific NbS interventions that are described in detail in Section 4.
3	Climatic conditions	Are based on the "Köppen-Geiger climate classification" presented by (Beck et al., 2018). The map was transferred to ArcGIS software and the exact type of climate for each area (Criterion 1) was identified.
4	Scale of the study's target	That covers different levels of the study from city to neighborhood.
5	The study's primary focus	This helped us to investigate broad and narrow concepts related to NbS and the main objective of the research. To better understanding and consensus, we referred to glossaries presented by (Nassary et al., 2022; Nehren et al., 2023).
6	Sectors	Relevant or responsible sectors that are important in developing NbS in urban areas and mentioned in the articles.
7	Adaptation measures	It was assigned to each article based on the adaptation measures through NbS given by (IPCC, 2022b).
8	Ecosystem services	For this criteria, we rely on a comprehensive list of ecosystem services suggested by (Yang et al., 2022).
9	Co-benefits	Each adaptation measure provided by NbS has several co-benefits to other measures, mainly for urban climate resilient development with deferent levels of evidence and agreement (IPCC, 2022b). We analyzed the data based on the sub-criteria given in (Table 6.6) of IPCC 2022b.
10	Linkage to mitigation measures	As NbS contributes to reducing GHG emissions, its linkage to mitigation should not be neglected (IPCC, 2022a).

the taxonomy in more detail in Sections 4.3, 4.4 and 4.5 and discuss them in Section 5.

4.3. Geographic distribution of NbS concepts across different climate conditions

Fig. 7 illustrates the global distribution of the NbS approaches. For example, the SC concept was initiated mainly in China, and it is evident that this concept is mainstream in the country. Likewise, GI and LID are more rooted in the US scientific literature. SUDS are widely used in North America, South America, Europe, China, Australia, and Africa. On the other hand, the distribution of NbS interventions in 290 cities worldwide is shown in Fig. 8. Melbourne (Australia) and seven cities in the USA: New York City, Austin, Philadelphia, Portland, Seattle, Cincinnati, Ohio, Xi'an (China) and So Carlos (Brazil) are the ten cities with the most frequently studied NbS. In addition, the USA, China, the UK, Australia, Italy, Spain, Brazil, Germany, Denmark, and South Korea had the most publications on the topic, with 202, 148, 62, 42, 42, 33, 32, 20, 19, and 19 papers, respectively. The results indicate a lack of research across a large part of Africa, which primarily includes the tropical and arid regions. as a large country, is noticeably missing from our search and analysis, and Iceland and other large countries such as Turkmenistan and Kazakhstan have not yet received attention. However, this could be due to the limitating the search to English-language documents.

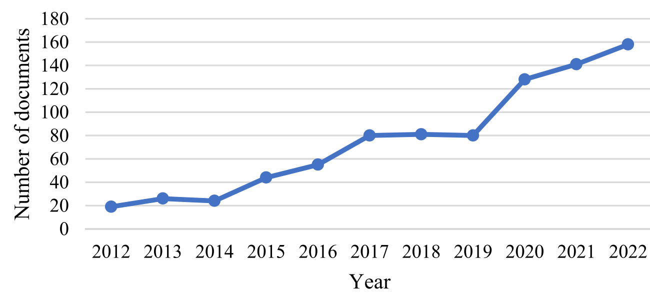

Fig. 4. Publication trends on the subject.

4.4. Interventions/practices, scales, and sectors

Literature articulates the aspects and functionalities of NbS at different levels. For instance, in GI planning and assessment, considering different spatial scales from watershed to single objects or individual interventions is necessary to better understand and model the functions and characteristics of ecological and urban areas (Arthur & Hack, 2022; Liu et al., 2024). According to Figs. 4 and 6 derived by DCA, various scales were considered based on the purposes of the research. City-scale studies encompassing the entire city or metropolitan area. Urban scale refers to the characteristics of urban areas in cities and towns, including various aspects of human settlement, built environments, population, land use land cover, infrastructure networks, and buildings. Additionally, the terms urban catchment, watershed, and basin are often used interchangeably in the context of urban hydrology, water resources, and

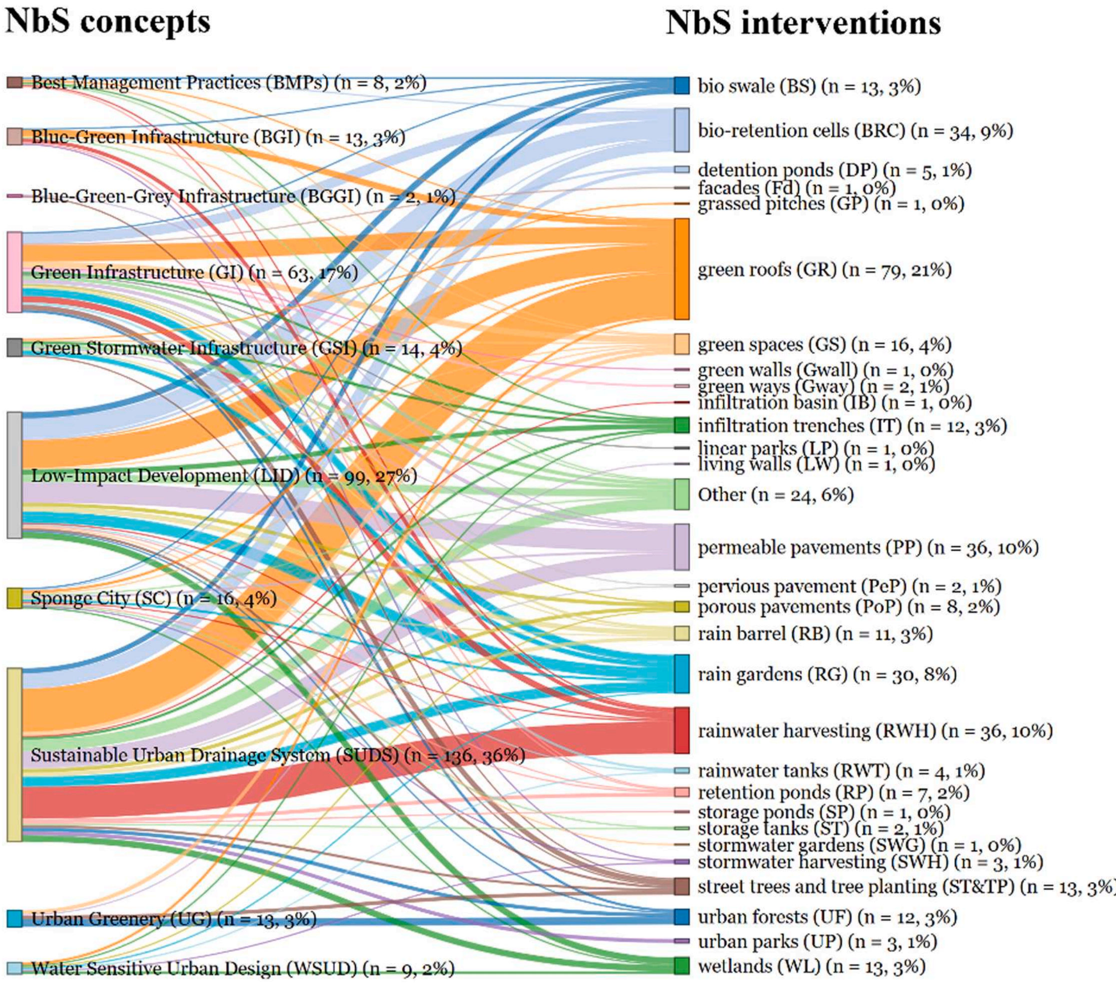

Fig. 5. Concepts of NbS and associated interventions/practices created by authors using "Display R" software.

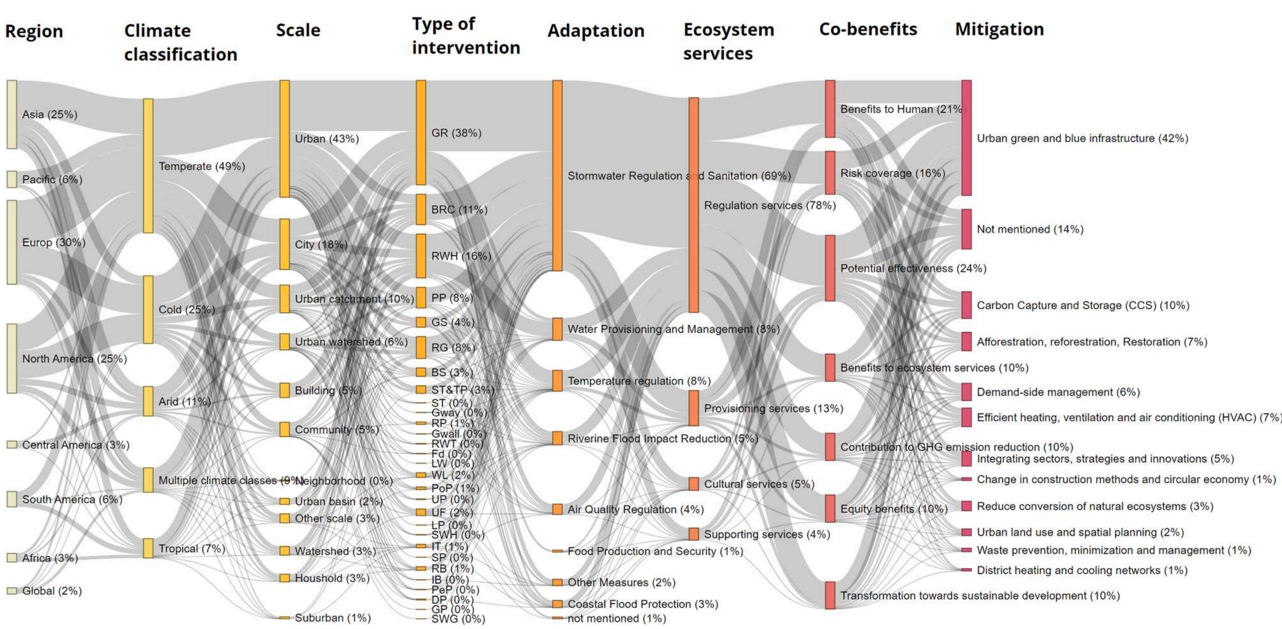

Fig. 6. Sankey Diagram of NbS Taxonomy created by the authors using "Display R" software.

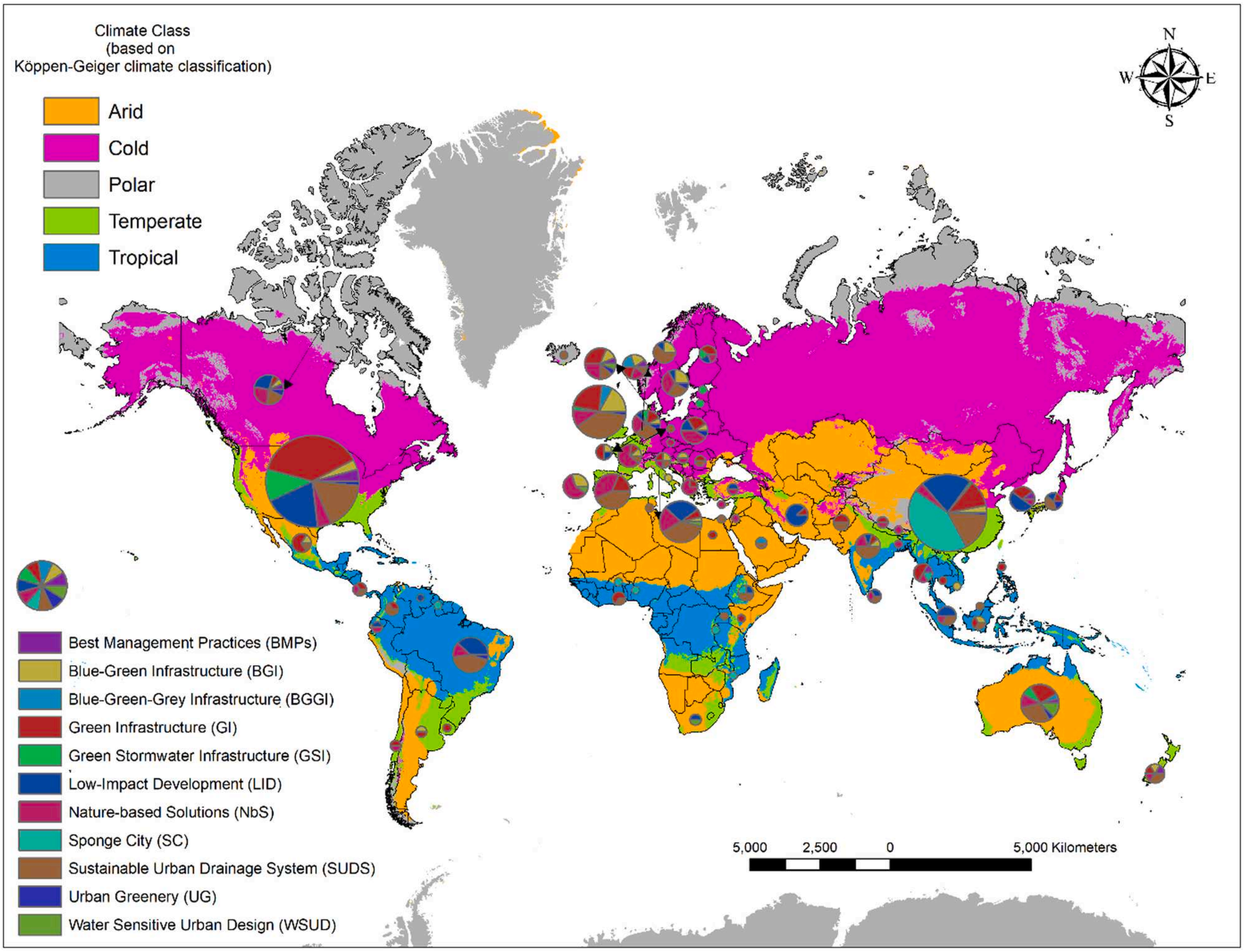

Fig. 7. Geographic distribution of NbS approaches in the world and across different climatic conditions.

ecological planning. However, they can have different spatial extents and sizes based on the hydrology and drainage systems of a specified area. A watershed refers to smaller river drainage as part of a larger river drainage area (basin) (Steiner et al., 2000). Moreover, urban catchments mainly refer to impervious coverage of urban areas such as roads, pavements, parking lots, and rooftops. The prevalence of imperviousness due to a mix of man-made and natural surfaces disturbs the hydrology of the area and contributes to increased surface runoff and water accumulation (Jacobson, 2011; Salvadore et al., 2015). Therefore, catchment scales are usually considered to study the stormwater caused by imperviousness, whereas basin scales refer to broader urban development and hydrological studies (Yang et al., 2011). Fig. 9 shows the distribution of various types of NbS across different scales and sectors. This demonstrates the frequency with which specific interventions have been studied on different scales and related sectors. For instance, the urban scale is subjected to the study of most NbS interventions, followed by the city, urban catchment, urban watershed, and community scales. The order of interventions across all scales was green roofs, rainwater harvesting, bioretention cells, permeable pavement, rain gardens, green spaces, and urban forests. It can also be seen that some building-scale studies focused on green roofs and rainwater harvesting. However, some scales, such as neighborhoods and suburbs, are not dominant in NbS studies.

The definition and governance of urban water sectors, including stormwater management, have evolved significantly in recent years. Urban water management addresses the challenges of managing urban drainage systems, contributing to nature conservation and sustainability and extreme weather-related disaster risk reduction (Mishra et al., 2020). It has also been suggested that stormwater management should be integrated into urban planning processes with close collaboration among a diverse set of actors (Bohman et al., 2020). From the perspective of smart, resilient, and sustainable cities, stormwater is considered an underutilized resource that can resolve water quality and quantity challenges (Cousins, 2018). However, sustainable stormwater management and its challenges are associated with urban governance/policy and its solutions, such as co-governance and stakeholder involvement (Qiao et al., 2018). Therefore, stormwater management is a critical component of both urban governance/policy/planning and water resource management and requires a holistic approach that integrates various governance structures and policy instruments. Based on our results, the sectors with the most links to NbS interventions are listed as urban governance/policy/planning, urban BGI/forestry, water resources and management, landuse planning, and disaster management. Also, several sectors were not extensively linked to NbS. For instance, the health and economy sectors do not seem to be engaged in the research and implementation of interventions. Other less considered sectors are building, education, transportation, tourism, and waste management, with a minimum number of studies.

Overall, it appears that researchers intend to discuss NbS mainly at an urban scale and in the context of urban planning. This could have implications for future research and implementation, as scaling up or down is required to further develop previous empirical experience in urban environments. This is consistent with previous studies showing that NbS are generally more effective when integrated into large-scale

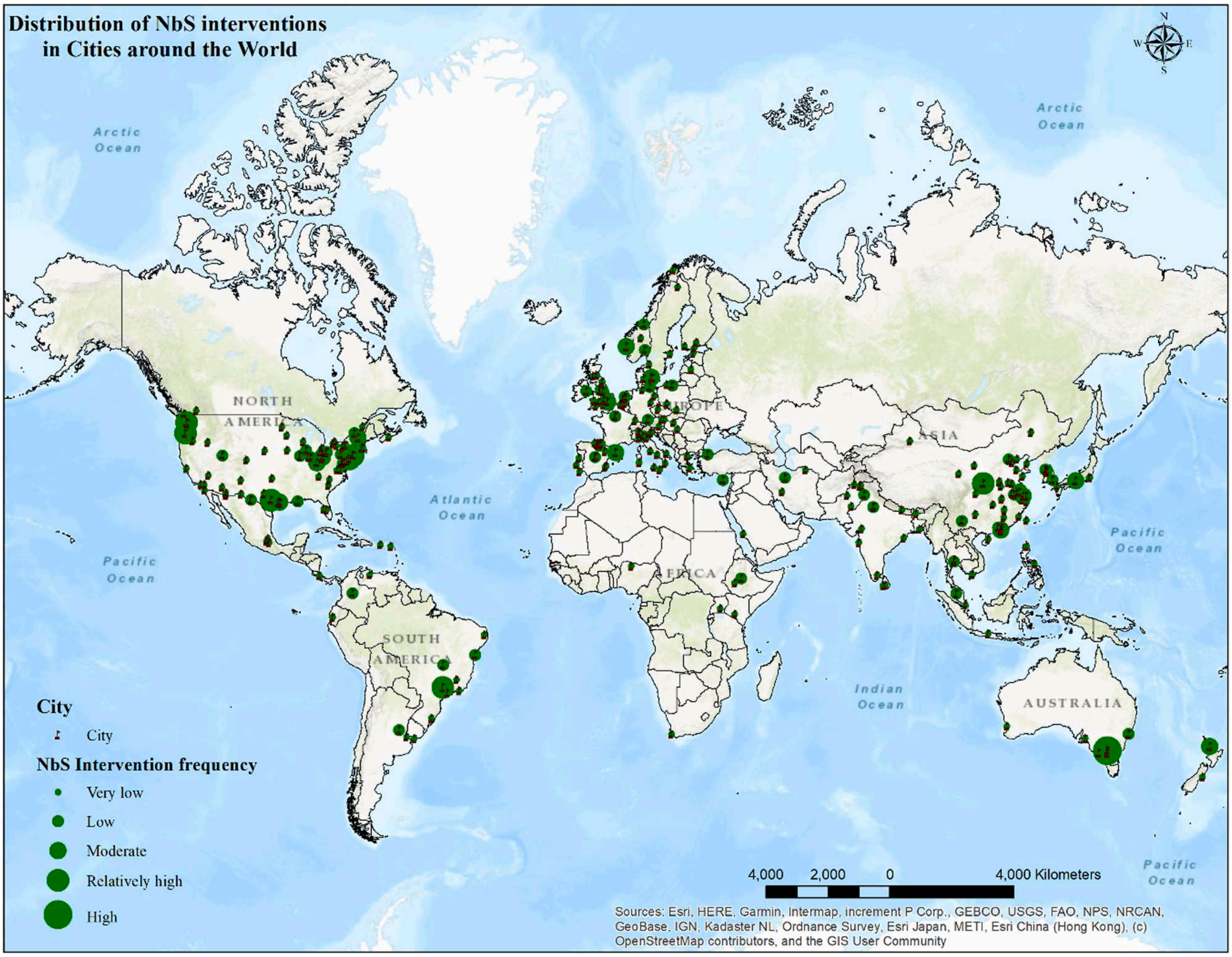

Fig. 8. Distribution of NbS interventions in 290 cities around the world.

landscape-based and networked interventions in cities (Peng et al., 2022; Zandersen et al., 2021).

Furthermore, the dominant sectors shown here could be effective in planning and allocating NbS (Camarasa et al., 2022). Additionally, by engaging multiple sectors in research, more insights and advances can be delivered to the planning and implementation of NbS.

4.5. Adaptation, mitigation, ecosystem services, and other co-benefits

As shown in Fig. 6, 69% of the reviewed papers focused on stormwater regulation and sanitation as their primary adaptations. Additionally, Fig. S4 (Supplementary material) presents the papers' focus on the types of interventions and their corresponding functions. Previous research is also consistent with our analysis and highlights the significant contribution of NbS in addressing urban water challenges, such as surface runoff and urban flooding (Xu et al., 2022). Other adaptation measures to which NbS contribute include water provisioning and management, temperature regulation, reduction of the impact of river flooding, air quality regulation, coastal flood protection, and food production and security, accounting for 8%, 8%, 5%, 4%, 3%, and 1% of the reviewed papers, respectively. Furthermore, 3% of the reviewed papers did not fall into these categories. Despite the multiple co-benefits of NbS and GI for climate change mitigation (Sharifi, 2021), there has been comparatively less focus on mitigation in the reviewed literature. The most dominant mitigation components mentioned in the reviewed studies were carbon capture and storage. Additionally, the most significant potential contributors to mitigation mentioned in the papers were urban forests, green spaces, green roofs, street trees, and tree planting. However, bioretention cells are the first among most mitigation measures.

Among the categories of ecosystem services that NbS can provide, regulation services (carbon sequestration, climate regulation, air purification, hydrological regulation, water purification, water conservation, disturbance regulation, soil retention, biological control, waste treatment, nutrient retention, and coastal protection) are the most discussed in the literature (78%). Other ecosystem services, such as provisioning (food production, water yield, raw materials, and net primary production), cultural (cultural and recreation), and supporting services (biodiversity and nutrient recycling), were mentioned in 13%, 5%, and 4% of the papers, respectively. Green roofs and rainwater harvesting are considered multifunctional, primarily for hydrological regulation, water yield, and climate regulation. Other interventions provide one or more services such as bioretention cells, permeable pavements, rain gardens, wetlands, and green spaces. Emphasis on stormwater management was revealed in our analysis. The soil-related functions of interventions such as permeability, infiltration, and filtration could significantly affect their effectiveness in stormwater management (Minixhofer & Stangl, 2021).

In addition, 30% of the reviewed studies reported the co-benefits of NbS, apart from their primary adaptation objective. These include benefits to human health and livelihood (23%), risk reduction (14%), equity (9%), transformation toward sustainable development (9%), ecological protection (8%), and GHG emission reduction (8%). Among the specific interventions/techniques, green roofs, rainwater harvesting, bioretention cells, permeable pavements, and rain gardens were found

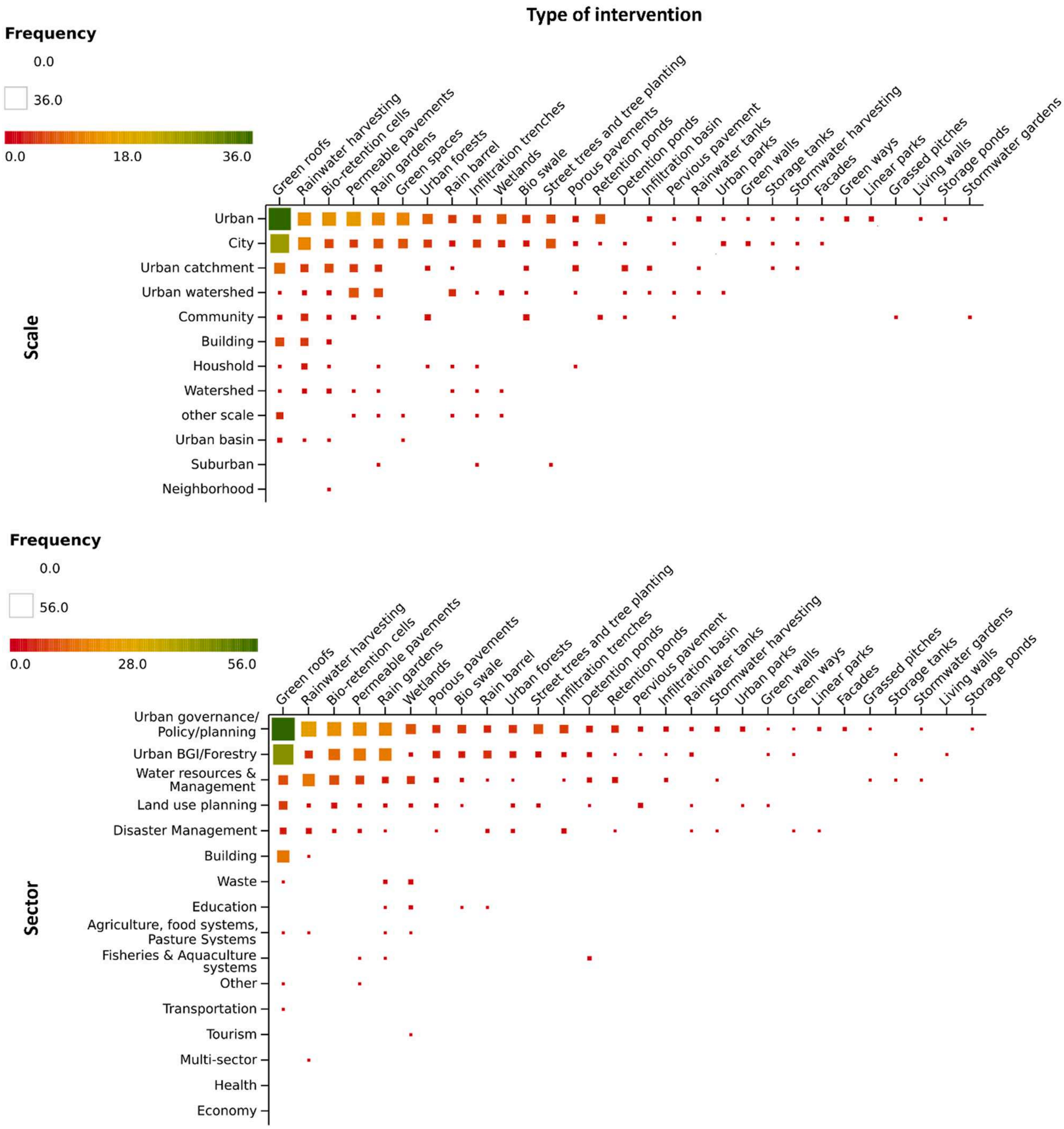

Fig. 9. Specific NbS interventions and associated scales and sectors.

to contribute the most to adaptation, mitigation, ecosystem services, and other co-benefits.

5. Discussion

5.1. On the taxonomy for highlighting NbS holistic value; how NbS can be varied in different geographies?

Different NbS concepts can be defined for different purposes. For example, in many places, LIDs are designed to control the quantity and quality of aquatic systems (Shannak, 2021). However, it has been shown that different cities, locations, demographic conditions and community perceptions can influence preferences for implementing interventions and their co-benefits (Spahr Katie et al., 2021). In many African countries, the primary focus is on water security and management through rainwater harvesting and adaptation to extreme water challenges. Attempts have been made to understand and use NbS in Benin, Burkina Faso, Egypt, Ethiopia, Ghana, Kenya, Mozambique, Rwanda, South Africa, Tanzania, and Uganda. Therefore, it is necessary to consider the context of research and practice when implementing NbS. For example, the hydrological performance and runoff reduction capacity of green roofs vary depending on the intensity and duration of the rainfall (Liu et al., 2021). Also, a comparative study between China and the USA by Xu et al. (2022) confirmed that the design parameters of SC components can be significantly influenced by climate, geographical environment, and socioeconomic conditions. Because the proposed taxonomy links these contextual factors, it can also be useful in NbS design.

In each region or country, there could be different contexts in which NbS is defined, socio-ecological systems and challenges addressed, and policies adopted to implement NbS (Dan et al., 2023). Therefore, as China has introduced the SC concept, countries may consider different approaches to integrating NbS into policymaking, urban planning, the built environment, and so on (Guan et al., 2021). NbS can go beyond a specific goal, such as stormwater management, for regions with different climates and urban systems. For example, eight studies focused on Norway and bioretention cells, green roofs, BGI, LID, rainwater harvesting, and rain gardens. Studies in Denmark have examined green roofs, GI, living walls, permeable pavements, and WSUD. In Sweden, concepts such as BGI, SUDS, NbS, and UG are considered more commonly. Bioretention cells, green roofs, GSI, and NbS have also been investigated in Finland.

Fewer studies in Bergen and Tromsø (Kvamsås, 2023) which are in the middle and north of Norway, and Kiruna in northern Sweden (Zischg et al., 2018) (as also shown in Fig. 6) with arctic climate conditions show the motivation/demand/implementation potential and call for research on NbS in this region for knowledge transfer and expansion. Joint activities have been carried out over the last decade by the Arctic Council (including Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the USA) through the Protection of the Arctic Marine Environment (PAME) program. Their ecosystem-based management framework (EBM) aims to provide ecosystem services, guide and protect marine ecosystems, and strengthen the resilience of indigenous populations and other socio-economic factors, such as tourism and trade (PAME; UNEP). This can potentially be viewed as a context-specific NbS for the Arctic region with particular climatic conditions. Furthermore, it can offer solutions to address the vulnerability of local inhabitants to global changes. Another example is the collaborative research and practice between Russia and the UK to promote NbS for climate change adaptation and mitigation. These research and knowledge transfer programs include research recommendations and cooperation priorities for implementing NbS in Russia (Paul Sayers et al., 2021). Further details of other criteria, such as climate classification, region, and country associated with NbS, can be found in the Online Supplementary material (Fig. S1, S2, and S3).

5.2. Planning and management perspective for NbS

Consistent with our results, previous studies have shown that urban, city, and urban catchments are the three dominant scales for NbS (Peng et al., 2022; Zandersen et al., 2021). Community and urban watersheds were the subsequent common scales based on the DCA in the current study. It is suggested that city scale is preferable for research and development because NbS are generally more effective when incorporated into large-scale, landscape-based, and interconnected interventions in cities as a whole. This argument has also proven to be applicable in NbS planning by some empirical studies for instance (Peng et al., 2022; Zandersen et al., 2021). However, few studies have suggested the potential of building-oriented NbS approaches for mitigation co-benefits. For example, great potential for NbS adoption in buildings and their surroundings has been reported in the European context (Bona et al., 2023). Some studies have shown how to scale up NbS approaches, such as SC, from the city scale to the watershed scale as an integrated solution for restoration and conservation beyond the city boundary (Wang et al., 2021). Furthermore, by studying at the watershed scale, we can assess broader aspects, such as biodiversity, recreation, and flood management, and better understand their potential and capabilities in each region. For instance Arthur and Hack (2022), through a multi-scale approach, revealed how different functions, types, and characteristics of GI can be identified by incorporating data on multiple scales from watersheds to neighborhoods and single objects. Taking into account the broader scale, such as watersheds or large cities as a whole area of interest, enables us to consider the potential of surrounding and suburban ecosystems to be engaged in the planning and implementation of NbS (Liao et al., 2024). In turn, this can prevent fragmentation of green spaces (Yeo et al., 2022). Furthermore, the DCA results show that the key sectors that can effectively plan and implement NbS are urban governance/policy/planning, urban BGI/forestry, water resources and management, land use planning, and disaster management. We propose involving multiple sectors in developing strategic plans based on local circumstances and priorities.

Some studies, for instance Dubo et al. (2022), argued that NbS values should not be limited to addressing specific climate hazards, such as floods or droughts. Through the current study that discovered various links between functions of NbS, we argued that it is better to not lose opportunities in the strategic planning of NbS and enhance resilience and sustainable development by considering local climate conditions and other co-benefits. In this regard, understanding short- and long-term NbS responses under climate-induced pressures is essential. Additionally, barriers and enablers to scaling up NbS interventions must be identified in different areas and under socioeconomic conditions. For example, despite the numerous benefits and diverse range of ecosystem services provided by NbS, it is important to note that they may also cause adverse effects and disruptions in city environments (Hérivaux & Le Coent, 2021). These issues are mainly reflected in residents' perceptions of green spaces and their concerns about pests (e.g., rats and mosquitoes) and litter (Williams et al., 2019). Therefore, trade-offs likely caused by natural ecosystems in urban areas are a concern that future research should consider. Exploring likely spatial trade-offs should not be ignored when implementing interventions and assessing their performance (Rodriguez et al., 2021; Sharifi et al., 2021) and their equal distribution for adaptation capacity across cities or urban areas (Song et al., 2019). In addition, for the optimal design and management of NbS in urban settings, the spatial configuration of interventions should also be an essential factor (Le Floch et al., 2022) as it could be essential to maximize the co-benefits and thus improve physical and mental health (Chen et al., 2022; Rodriguez et al., 2021).

Should NbS types be implemented as single and separated interventions or should they be combined as complementary systems? Our study attempted to connect concepts and interventions and their functions in ecosystem services (i.e., air regulation, climate regulation), adaptation (i.e., stormwater regulation and sanitation, air quality regulation), mitigation (i.e., carbon capture and storage), and other co-benefits (i.e., benefits to humans and transformative benefits). Our results suggest that the synergistic values and combined configuration of NbS in different locations should be examined, as the links were shown in the proposed taxonomy. For example, Shetty et al. (2022) demonstrated the effectiveness of combining rainwater harvesting and green roofs in responding to extreme climate events in urban drainage systems. Moreover, it is suggested that the design and implementation of NbS are objective-oriented. For example, a range of NbS can be used for specific goals, such as bioretention cells to maintain water quality resilience, permeable pavements, green roofs for flood resilience, and rain barrels for residential water supply, while considering their inter-multifunctionality. Additionally, Duffaut et al. (2022) recommended diversifying NbS to maintain its functions and benefits in the face of urban disturbances. It is also important to consider the surrounding environment in NbS design.

5.3. Implications, limitations of the study, and future research recommendations

The proposed taxonomy highlights the potential of urban NbS, which can be diverse, pursue multiple objectives, and be multi-functional. This methodology allows planners and policymakers to gain an overview of NbS implementation by categorizing different types of NbS and understanding their associations in different contexts. It may also be helpful in creating more detailed and useful frameworks for the adaptation potential of NbS. This study concluded that NbS has gained significant attention during the last decade, and the number of studies has increased annually. This means that researchers, practitioners, and policymakers have increasingly recognized the potential of NbS. However, the complexities of NbS dynamics and mechanisms remain relatively unexplored. Therefore, the various adaptation and mitigation measures, sectors, scales, geographic distributions, and ecosystem services discussed in this study require future research. As a limitation of this study, we acknowledge that it is only based on peer-reviewed literature written in English. Considering other languages and analyzing gray literature may provide more information.

Over the past decade, researchers worldwide have focused on the benefits of NbS in addressing climate-related challenges in densely populated areas. Understanding how NbS may be affected by climate change, considering both global and contextual factors, should not be neglected. However, future changes in the physical, environmental, and societal conditions of cities are inevitable. These emerging challenges should be prioritized in future research on NbS. For example, urban population growth and rapid expansion of cities in many developing countries, as well as reliance on established engineering solutions, continue to hinder policy design and implementation. Other aspects, such as increasing temperatures, rising costs, and lack of knowledge or commitment, could also be considered. While NbS offer promising solutions to climate change issues, future research and efforts are needed to fully harness their potential and ensure their effectiveness in addressing societal challenges comprehensively. Additionally, more lessons learned from case studies are required to establish practical solutions based on different contexts and local knowledge. Justice and equity issues also require more attention in terms of planning and implementation. Future research must encompass transdisciplinary approaches to NbS and develop the scientific basis, including the performance evaluation of single and hybrid types for specific challenges. It could also be explored how technological advancements can enhance the implementation and capacity of NbS in both research and practice. Knowledge transfer from pioneer regions in NbS implementation and practical methodologies for promoting NbS in less developed countries where NbS is not yet fully utilized and most needed should be considered. Forthermore, experimental tests on valuable types of NbS and case studies (modeling, simulation, and performance assessment) in underexplored regions are needed. In addition, trade-offs, synergies, co-benefits, and conflicts between sectors and actors that adopt these solutions on different scales should be analyzed quantitatively and qualitatively. These efforts can help to establish local and national NbS design and implementation guidelines. The proposed taxonomy supports adaptation frameworks and encourages stakeholder engagement in strategic NbS planning. Thus, it can help policymaking initiate future actions.

6. Conclusions

Research in recent years has attempted to demonstrate the potential and capacity of NbS to address urban challenges. However, further studies are still needed to expand the existing knowledge for the optimal and effective implementation of NbS to cope and adapt to climate change. The motivation of the current research was to clarify how NbS are related to several contextual factors that could impact efforts to operationalize them in cities. We attempted to provide a clearer classification and description of NbS and its subcategories, which have not been defined in previous research. A DCA of 582 original case study articles was conducted. We have proposed a taxonomy of NbS to understand how NbS is designed and implemented across different cities, countries, regions, scales, and climates and what potential contributions to adaptation, ecosystem services, and other co-benefits are reported. The taxonomy includes hierarchies and categorizations that allow us to examine the relationship between NbS approaches and interventions and identify attributes/factors that contribute to their functionality, operationalization, and planning perspectives in the urban context. The current study concluded that SUDS is the most dominant among the NbS concepts, followed by LID and GI. In addition, green roofs, permeable pavements, rainwater harvesting, and bioretention cells are the most frequently assessed NbS interventions in the literature. There could be similarities between the definitions of the different types of NbS (concepts or interventions). However, they may differ in terms of their purposes and objectives (Table S1). Most of the reviewed articles were from Europe (30%), North America (25%), or Asia (25%). Countries such as China offer various approaches to integrating NbS into urban planning, built environments, and policies. However, some regions, such as Africa's tropical and arid areas, which are undergoing major urban transformation, are underexplored. The Middle East also requires more attention in research on NbS. However, ecosystem service management in the Arctic region offers insights for promoting NbS in challenging areas with special climatic conditions. The findings emphasize the effectiveness of large-scale, interconnected interventions in urban, city, urban catchment, and watershed scales. Studies at the watershed scale may provide more insights related to the multiple benefits of NbS, as they discuss peri-urban ecosystem features in a broader area. City context and demographics affect preferences, requiring context-sensitive NbS for optimal results, including spatial trade-offs and health benefits. Case studies should also guide context-specific practical solutions by focusing on justice, equity, and local NbS design and implementation guidelines.

CRediT authorship contribution statement

Kamaleddin Aghaloo: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Ayyoob Sharifi**: Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Nader Habibzadeh**: Formal analysis, Data curation. **Tausif Ali**: Formal analysis, Data curation. **Yie-Ru Chiu:** Formal analysis, Data curation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Paperpal to check the grammar, punctuation, and clarity. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128320.

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