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Nature-based solutions in arid and semi-arid countries: A review of best practices and lessons learned

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ABSTRACT

Arid and semi-arid regions are defined by low annual precipitation, which contributes to chronic water scarcity and frequent severe drought events. In recent years, climate change has exacerbated these challenges, causing more frequent and intense rainfall events, which increase flood risk, particularly in highly urbanized and densely populated areas, followed by prolonged drought periods. To mitigate both water scarcity and flood effects, several nature-based solutions, commonly used in humid areas, have been readapted and implemented in arid and semiarid climates. Specific guidelines and directives for their implementation in these contexts are, however, not available nor well defined. Based on well-established real applications, this work presents a literature review of the most efficient and commonly used nature-based solutions installed in arid and semi-arid areas. The geographical distribution, the main purpose, the structure, and the vegetation chosen in real case studies have been assessed through a systematic analysis of 89 papers. Results highlight frequent use of green roofs, rain gardens, and water harvesting systems in these regions. The findings of this research could serve as a valuable reference for other cities with similar climatic conditions and support the global promotion and adoption of green infrastructure, particularly in arid and semi-arid regions.

1. Introduction

Nature-based solutions (NbS) are increasingly recognized as sustainable approaches to address diverse societal challenges, ranging from climate change adaptation to urban livability (McPhearson et al., 2023; Nlend et al., 2025). According to the International Union for Conservation of Nature (IUCN, (Berg et al., 2024)), NbS are defined as “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016). In practice, NbS leverage natural processes and ecosystem services to provide multifaceted benefits across urban, rural, and coastal environments, spanning various climatic regions and socio-economic contexts (Lozano et al., 2025). By working with nature and reproducing the natural environment, these solutions aim to deliver win–win outcomes for both human communities and the environment, enhancing resilience while preserving or restoring ecosystems

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(Bianciardi et al., 2023).

NbS can take many forms, including ecosystem restoration and conservation, green infrastructure, and integrated landscape management strategies (Cohen-Shacham et al., 2016). Each approach is designed to address specific societal issues while delivering ecosystem services that enhance human and environmental well-being (Cohen-Shacham et al., 2016; Haines-Young and Potschin, 2012; Maes and Jacobs, 2017). For instance, reforestation, wetland restoration, and the rehabilitation of degraded land can combat desertification, improve soil quality, and increase water retention (Ait Elallem et al., 2021; Qian et al., 2024; Schuster et al., 2024). In urban areas, interventions like green roofs, urban forests, and permeable pavements can mitigate the urban heat island effect, absorb stormwater runoff, and improve air quality, while also providing habitats that boost urban biodiversity (Ashinze et al., 2024; Cristiano et al., 2021; Tun et al., 2025). Similarly, at the watershed or agricultural scale, practices such as integrated water resource management and agroforestry help optimize water use, ensure water security, and promote sustainable livelihoods for local communities (Roy et al., 2025; Zerga, 2025). These examples illustrate the versatility of NbS in bringing natural features and functions into engineered settings to tackle challenges ranging from drought and heat waves to flooding and pollution.

To qualify as NbS, an intervention must address one or more defined societal challenges and provide measurable ecosystem service benefits. The hallmark of NbS is this multifunctionality—delivering primary target outcomes (e.g., improved water availability or reduced heat stress) while simultaneously generating co-benefits like enhanced biodiversity, better air/water quality, and carbon sequestration (Ashinze et al., 2024; McPhearson et al., 2023; Seddon et al., 2020). This characteristic distinguishes NbS from conventional grey infrastructure solutions, which typically focus on a single problem in isolation. For example, a cooling challenge in a semi-arid city could be addressed with mechanical air-conditioning systems or, alternatively, by expanding green spaces (such as green roofs and urban parks) (Hobbie and Grimm, 2020). While the former (artificial cooling) offers immediate localized relief, the latter NbS approach not only lowers ambient temperatures but also improves air quality, supports urban biodiversity, and increases overall resilience to heat stress over the long term. Often, an optimal strategy involves a combination of grey infrastructure and NbS, blending immediate efficacy with sustainable, long-term co-benefits (Fennell et al., 2023; Seddon et al., 2020).

Designing and implementing effective NbS requires careful planning to balance ecological integrity with technical feasibility. International frameworks such as the IUCN Global Standard for NbS provide guidance to ensure that nature-based interventions are sustainable and appropriately tailored to their context (Andrade et al., 2020). Key principles include integrating NbS into broader systems (rather than deploying isolated one-off projects), maximizing resource efficiency, and adapting solutions to local environmental and socio-cultural conditions (Cohen-Shacham et al., 2019; Sowińska-Świerkosz and García, 2022). Adhering to such principles helps embed NbS within comprehensive strategies that address interconnected challenges such as water scarcity, biodiversity loss, and social equity. In essence, successful NbS should be systemic, resource-efficient, and locally adapted interventions that complement or enhance traditional engineering approaches (Cohen-Shacham et al., 2019)-Shacham et al., 2019.

Modern NbS approaches build upon a foundation of traditional knowledge, while harnessing advanced ecological and engineering techniques to achieve broader impact. Around the world, communities have long used nature-based or nature-inspired practices to increase their resilience – for example, terraced farming to reduce erosion or sacred groves preserved for watershed protection (Kosmowski, 2018; Sullivan et al., 2024). Many NbS that have been extensively studied and implemented in humid or temperate regions with milder climates could potentially be adapted for use in arid and semi-arid regions. However, there is currently a lack of specific guidelines or frameworks to assist decision-makers in selecting the most suitable and high-performing NbS for dryland environments (Alikhanova and Bull, 2023; Martin et al., 2025). This gap is especially pertinent for arid and semi-arid countries, where unique climatic extremes demand careful adaptation of NbS design and where evidence-based guidance for practitioners remains limited (Castaldo et al., 2025; Yimer et al., 2024).

Arid and semi-arid regions present a distinctive set of water-related challenges, but also opportunities for NbS to make a significant impact (Okello et al., 2024). In these water-scarce landscapes, nature-based interventions could play a crucial role in enhancing both urban and rural resilience alongside conventional engineering measures (Jongman et al., 2021; Pienaah et al., 2025; Yimer et al., 2024). Historical practices in such regions demonstrate that working with nature has long been a strategy for survival in harsh climates. For example, the creation of oases—through careful water harvesting and the cultivation of drought-tolerant vegetation—and the use of qanats (underground tunnel systems that tap alluvial groundwater) are early illustrations of sustainable water management tailored to arid conditions. These traditional systems effectively stored and distributed water, providing critical supplies during dry periods. They demonstrate how localized, nature-inspired solutions can address specific problems (like water storage and irrigation) effectively in extreme environments, foreshadowing the principles of modern NbS (Manuel et al., 2018; Nasiri and Mafakheri, 2015).

Despite these traditional adaptations, many arid and semi-arid regions today face worsening water insecurity under population pressure and climate change. Annual precipitation in such areas is not only low but also highly irregular and unevenly distributed (Dzvene et al., 2025; Morante-Carballo et al., 2022). For example, more than half of the Middle East and North Africa (MENA) regions receive an average of less than 100 mm of rainfall per year, whereas only about 18% of the region's area receives more than 300 mm (Droogers et al., 2012; Waha et al., 2017). Even in the relatively wetter highlands or coastal zones of MENA (which can get up to 1500 mm annually), a large portion of rainfall is lost to evaporation and rapid runoff (Ajjur and Al-Ghamdi, 2021). This means that effective precipitation available for ecosystems and human use is very limited. Moreover, climate projections indicate that average rainfall in many dry regions is likely to decrease further in coming decades, which would exacerbate the frequency and severity of droughts (Kenawy et al., 2025; Mohammed Qasem and Scholz, 2025). An increasing prevalence of below-average rainfall years and prolonged multi-year drought periods are expected to jeopardize water and food security in these areas (Kenawy et al., 2025; Khosravi and Ouarda, 2025).

Paradoxically, when rain does arrive in arid and semi-arid regions, it often comes in sudden, intense downpours that the landscape cannot absorb. Sparse vegetation cover and low soil water storage capacity mean that heavy rainfall quickly turns runoff rather than soaking into the ground (Aryal et al., 2020). As a result, flash floods are a frequent hazard even in places with very low total rainfall (Nabinejad and Schüttrumpf, 2023). These fast-moving floods can inundate settlements and infrastructure with little warning. They erode soil, damage roads and buildings, ruin crops, and pose serious risks to human life. For instance, many cities in the Middle East and North Africa experience dangerous flash flooding during rare extreme rainstorms despite otherwise dry conditions (Ghahraman et al., 2025). The twin threats of chronic water scarcity and episodic flood disasters—both of which are projected to worsen under climate change—underscore the urgent need for NbS that can bolster water security and mitigate flood risks in arid and semi-arid regions. By storing water when it is available and attenuating runoff during storms, well-designed NbS could help smooth.

Although existing reviews have largely contributed to advancing the understanding of NbS potential in arid and semi-arid regions, they primarily focus on specific sectors, such as agricultural applications (Bagwan, 2024), water management (Okello et al., 2024) and ecosystem restoration (Gorain et al., 2025), or are restricted to particular geographical contexts, including Africa or the Middle East and North Africa region (Alikhanova and Bull, 2023; Ben Hassen and Hageer, 2025a, 2025b; Gebrael et al., 2024). As a result, there is still a lack of integrated assessments examining how NbS can simultaneously address the interconnected challenges of water scarcity, drought resilience, and flash flood mitigation across different arid and semi-arid environments under extreme hydro-climatic conditions. In addition, limited attention has been given to the practical implementation and performance of NbS in arid environments, including considerations related to scalability, local adaptation, vegetation suitability, and long-term resilience. Consequently, decision-makers and practitioners still lack comprehensive guidance for selecting and adapting NbS strategies that are both effective and context-sensitive in dryland regions.

To this end, a comprehensive structured global analysis was developed that systematically collected and analyzed information from the selected case studies located in arid and semiarid regions only, with a focus on urban areas, enabling the quantitative assessment of key NbS characteristics and implementation outcomes. Specifically, data were categorized according to geographical location, environmental context, addressed challenges, NbS typology, vegetation characteristics, reported benefits, and implementation scale. This approach allowed for a consistent comparison of successful projects across different arid and semi-arid regions and provided a robust basis for identifying common trends, effective practices, and knowledge gaps related to NbS implementation under dryland conditions.

To address these knowledge gaps, this review investigates the potential of NbS to enhance climate resilience in arid and semi-arid regions, with particular emphasis on water scarcity, drought mitigation, and flood control in urban areas. Building on the structured analysis of case studies presented above, we evaluate the effectiveness of different NbS interventions in dryland environments and discuss their implications for sustainable water management and climate adaptation. The findings aim to provide evidence-based guidance for policymakers, water managers, and urban planners seeking to implement suitable NbS strategies in arid regions.

The remainder of the paper is structured as follows: Section 2 describes the methodology used to survey the literature and identify relevant case studies of NbS in arid/semi-arid regions. Section 3 presents an overview of the collected NbS examples, including their geographical distribution, types of interventions, the primary societal challenges they address, and the typical vegetation or ecosystem components involved. Section 4 discusses the results, highlighting key lessons learned and offering recommendations – potential guidelines and considerations – for effective NbS implementation in dry regions. Finally, Section 5 draws the main conclusions of the study and outlines future research needs, as well as practical gaps that should be addressed to better support NbS deployment in arid and semi-arid areas.

2. Methodology

The review was conducted through structured literature research of scientific publications on the application of NbS in arid and semi-arid regions. Bibliographic research was performed using Google Scholar and Web of Science, which were selected to ensure broad coverage of peer-reviewed scientific publications across environmental, engineering, and sustainability disciplines.

The literature search was carried out using combinations of keywords related to NbS and dryland environments, including: "Nature-based Solutions", "arid regions", and "semi-arid regions". Boolean operators (AND, OR) were used to combine search terms and refine the results. Only peer-reviewed journal articles written in English were considered. Conference papers, book chapters, reports, and non-scientific publications were excluded to ensure consistency and scientific reliability. This initial search yielded more than 300 articles. The records were then screened for relevance and for the presence of concrete NbS applications (including specific practices and typologies). A screening process was subsequently conducted in multiple stages. First, duplicate and clearly irrelevant studies were removed based on titles and abstracts. The remaining articles were then evaluated through full-text assessment to verify their relevance to the objectives of the review. Studies were included only if they presented concrete NbS applications, implemented practices, or case studies specifically related to arid or semi-arid environments. Articles focused exclusively on theoretical discussions without practical application examples were excluded. Following this refinement process, a final dataset of 89 peer-reviewed articles was selected for detailed analysis.

The selected studies spanning globally in arid and semiarid regions were analyzed through a multi-step classification framework designed to identify geographical, climatic, and technical patterns in NbS applications, with a special focus on NBS applied in urban context. First, all case studies were categorized according to their geographical location (Asia, Europe, Africa, America, and Australia) to evaluate the global distribution of NbS implementation in dryland regions. In addition to the continental-scale classification, the identified urban NbS were also aggregated at the country level to provide an overview of their adoption and representation within different national contexts. This level of analysis was intentionally considered separately from the climatic classification adopted in the review, as it reflects the policy and governance frameworks in which NbS are planned, funded, and implemented. National regulations, strategic priorities, and incentive schemes can play a significant role in promoting or hindering the uptake of NbS. Therefore, the country-scale assessment was used to complement the climate-based analysis and to provide additional insights into the geographical distribution and implementation potential of urban NbS. Second, each case was classified according to climatic conditions using mean annual precipitation as a simplified indicator of aridity. Following the classification proposed by Huang et al. (2021), regions with annual precipitation below 200 mm were categorized as arid, while regions receiving between 200 mm and 400 mm were classified as semi-arid. Although aridity is more comprehensively characterized through combined indicators that incorporate evapotranspiration (e.g., aridity index), mean annual precipitation was used as a proxy due to its consistent availability across the selected case studies. Additional information was extracted from each study, including type of NbS intervention, primary environmental challenge addressed, vegetation characteristics, irrigation practices, water management strategies, and reported environmental or resilience-related outcomes. This classification framework allowed the identification of recurring implementation patterns and context-specific adaptation strategies.

To identify the main research trends within the selected literature, a qualitative keyword frequency analysis was conducted using the author keywords reported in the selected articles. The analysis aimed to identify the most recurrent NbS typologies, environmental challenges, and management approaches discussed in studies focused on arid and semi-arid regions. Keywords with similar meanings were standardized to reduce redundancy and improve consistency in the analysis. The frequency of keyword occurrence relationships was examined to identify dominant research themes and emerging areas of interest. The analysis revealed that terms such as "nature-based solutions", "rainwater harvesting", "green infrastructure", and "green roofs" were among the most recurrent keywords, highlighting the strong emphasis on water management and climate adaptation strategies in arid and semi-arid environments.

Finally, each case study was examined to identify its primary objectives and the environmental challenges addressed, such as drought mitigation, flood control, water conservation, and climate resilience enhancement. This methodological framework enabled a comparative synthesis of NbS applications in arid and semi-arid environments, supporting the identification of implementation patterns, context-specific constraints, and research gaps relevant to future applications.

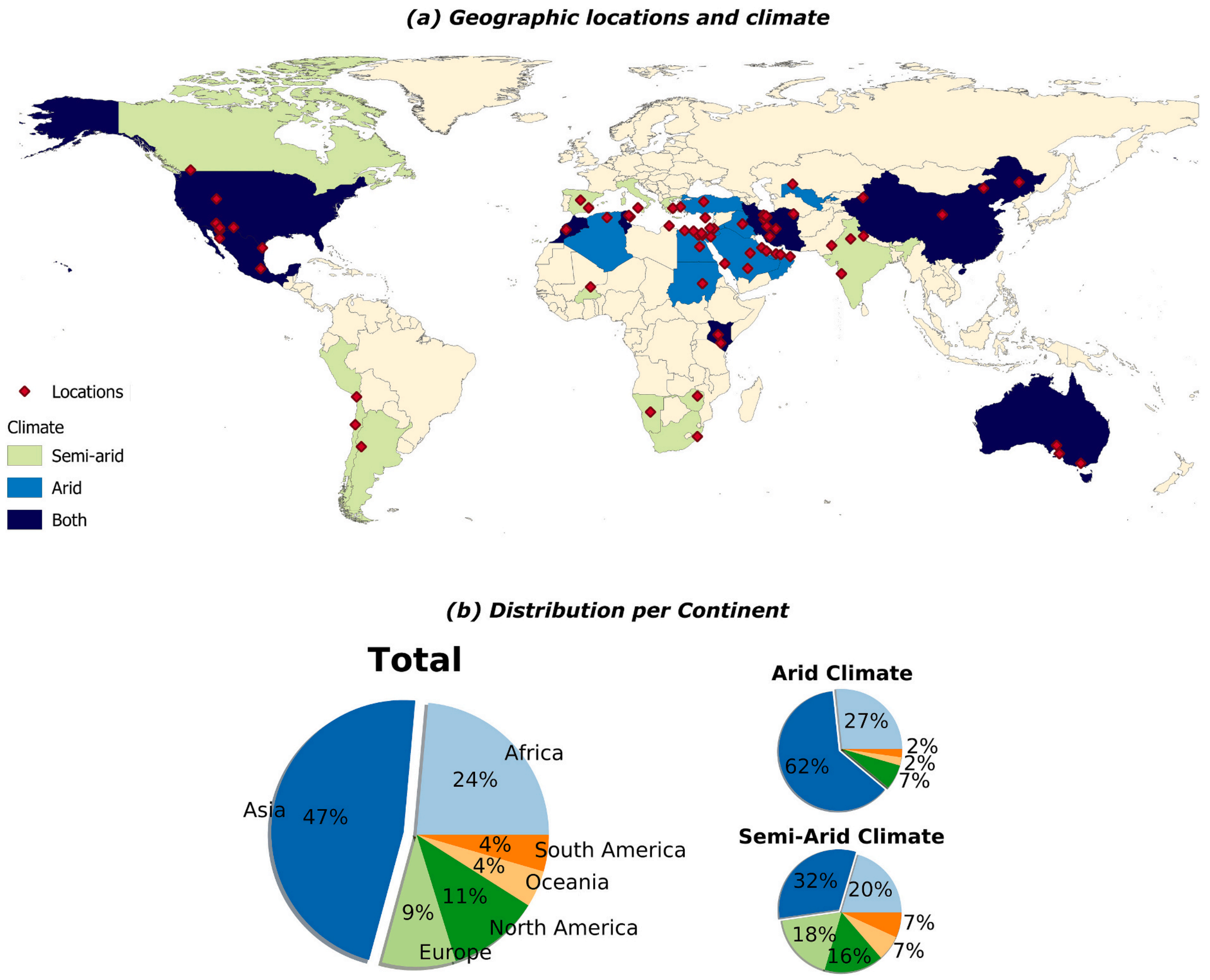

Fig. 1. NbS installation in arid and semiarid countries (a) Geographic location and related climate (b) NbS distribution per continent.

3. NbS in arid and semiarid areas

3.1. Geographical location

Among the 89 case studies included in the analysis, 45 are located in arid regions (meaning annual precipitation below 200 mm), while the remaining 44 are in semi-arid regions. The geographical distribution of cases is uneven, with significant concentration in the Middle East and North Africa, one of the most water-scarce and climate-vulnerable regions worldwide. Fig. 1a shows the geographical location of all 89 studies, highlighting whether the corresponding state is classified as arid or semi-arid. In the case of large countries spanning multiple climate zones, the classification was adapted according to the specific study location.

The majority of case studies are located in Asia (47%), a continent characterized by diverse climate types, including extensive arid and semi-arid zones. More than 60% of all arid-condition studies are situated in Asia (Fig. 1b). These regions face pressing challenges of drought and water scarcity, making NbS particularly relevant for water resource management and ecological restoration.

Africa represents the second-largest share, with 21 cases (24%), of which 57% are in arid areas. In particular, sub-Saharan Africa has long been affected by drought and desertification, with many countries heavily dependent on agriculture that is constrained by severe water scarcity. NbS applications in these regions largely focus on vegetation restoration, soil quality improvement, and water management as strategies to mitigate the impacts of climate change.

Smaller proportions of NbS applications in arid and semi-arid climates were identified in North America (11%), South America, Oceania (4%), and Europe (8%). These regions are characterized by a higher prevalence of humid and temperate climates, which partly explains the lower number of NbS cases targeting arid and semi-arid conditions.

3.2. Type of NbS

The review of NbS implemented within urban contexts of arid and semi-arid regions reveals a high variety of preferred solutions. The observed distribution patterns underscore the influence of climatic constraints, urban morphology, and spatial planning

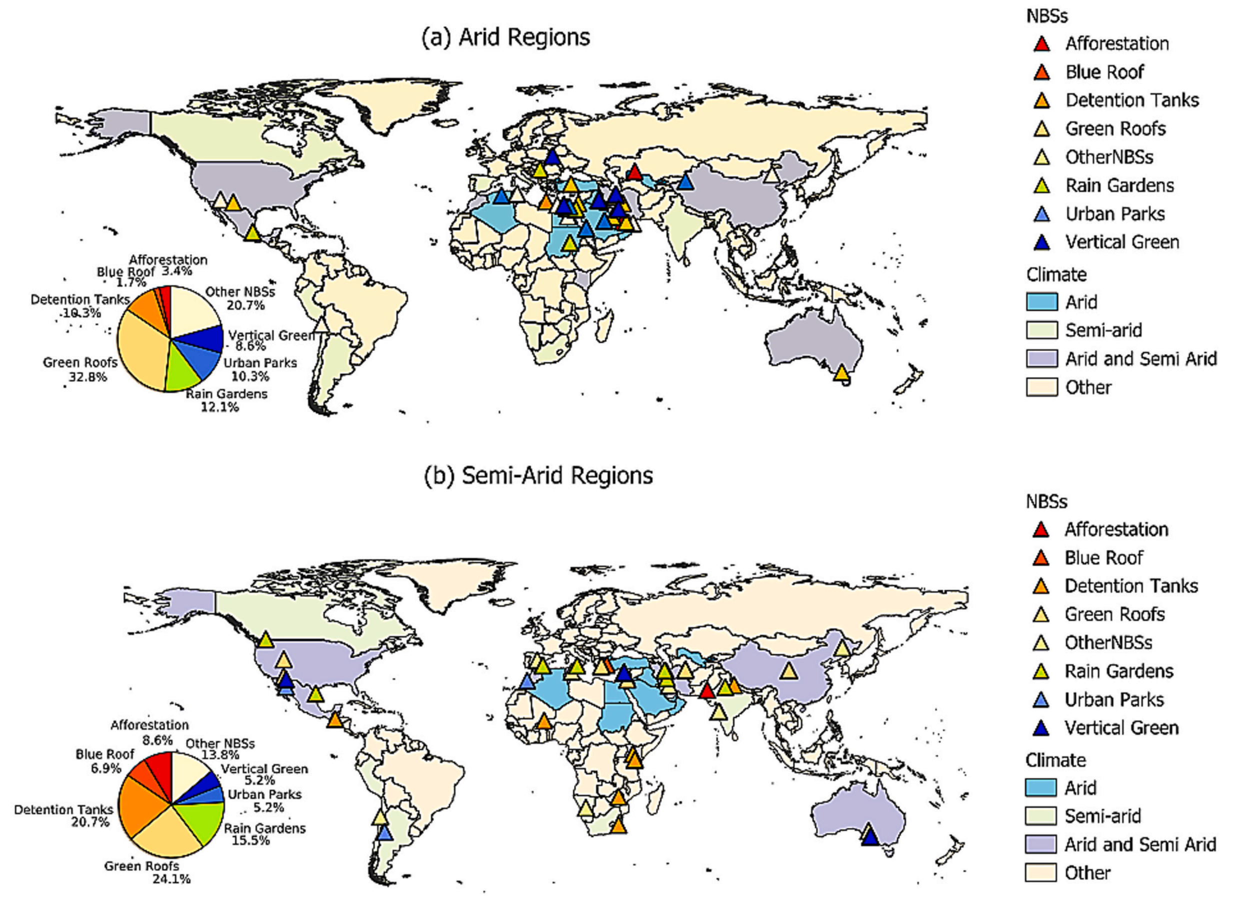

Fig. 2. Geographical and structural distribution of the different types of NbS in arid (a) and semi-arid (b) regions. A short description of the different NbS is included in the Supplementary Material S1.

considerations on the selection and deployment of NbS. Fig. 2 illustrates the geographic location and distribution of the different structures depending on the investigated climate.

Green roofs account for 33% of all NbS techniques in urban arid regions identified in this study, representing the most commonly investigated and applied solution. The second common NbS for arid regions are rain gardens (12%), followed closely by detention parks and urban parks (both 10%). Another common solution is constituted by vertical greening (9%), while other solutions, such as afforestation, are considered with a lower frequency, probably due to the high water demand.

Similarly, in semi-arid regions, green roofs also represent the most prevalent NbS (24%), followed by detention tanks (21%), highlighting the fact that, in these regions, issues connected to floods are more common. Other commonly used NbS are rain gardens (16%), blue roofs (11%), and afforestation (9%).

3.3. Societal challenges

According to IUCN, NbS can address seven major societal challenges: climate change mitigation and adaptation, disaster risk reduction, economic and social development, human health, food and water security, environmental degradation, and biodiversity loss. While NbS are often designed to respond to multiple challenges simultaneously, their selection and design typically begin with the identification of a primary challenge. In urban areas of arid and semi-arid regions, NbS most frequently target disaster risk reduction, particularly flash floods, and water security, especially in relation to drought.

As illustrated in Fig. 3, across the cases analyzed, 39% focus primarily on drought mitigation. This percentage rises to 61%, when droughts mitigation is combined with flood or water security issues. Besides drought mitigation, most of the studies focus on urban heat island and flood prevention, 15% and 11% respectively, confirming that these hazards represent the most pressing issues in dryland regions. The remaining studies addressed the NbS contributions in other sectors, such as urban greening, improved air quality, thermal comfort, and landscape restoration, underlining the multifunctionality of these installations.

3.4. Ecosystem services

As previously discussed, NbS inherently aim to address societal challenges through actions on natural or modified ecosystems. A central element of NbS is their capacity to generate and enhance ecosystem services, which represent the direct and indirect contributions of ecosystems to human well-being (Cohen-Shacham et al., 2016). Since NbS operate through the protection, restoration, and management of ecosystems, their synergy with the delivery of ecosystem services is intrinsic.

Ecosystems are complex systems characterized by multiple interactions and trade-offs, often delivering several services simultaneously. When compared to purely technological solutions, NbS may appear less efficient in the short term, as the latter are usually designed to optimize a single function (Remme et al., 2024). For instance, an air-conditioning system effectively regulates indoor temperature but entails high energy consumption and offers no additional benefits. A green roof, on the other hand, provides thermal regulation with lower efficiency when evaluated solely on that parameter, yet it also contributes to biodiversity enhancement and runoff reduction. Such co-benefits highlight the importance of integrated approaches, where technological and nature-based interventions can complement each other, maximizing overall performance while preserving ecosystem value.

The delivery of ecosystem services can thus serve as a concrete and robust methodological framework to identify, quantify, and value both the key and co-benefits of NbS. Through this lens, NbS can be more effectively compared with purely technological alternatives, as their multifunctional benefits become measurable and comparable within structured evaluation schemes. Economic valuation of ecosystem services, together with mechanisms such as Payments for Ecosystem Services (PES), provides tools for cost–benefit analyses that capture the broader social and environmental value of NbS.

Ecosystem services are commonly classified into three main categories: provisioning (nutrition, materials, and energy), regulation

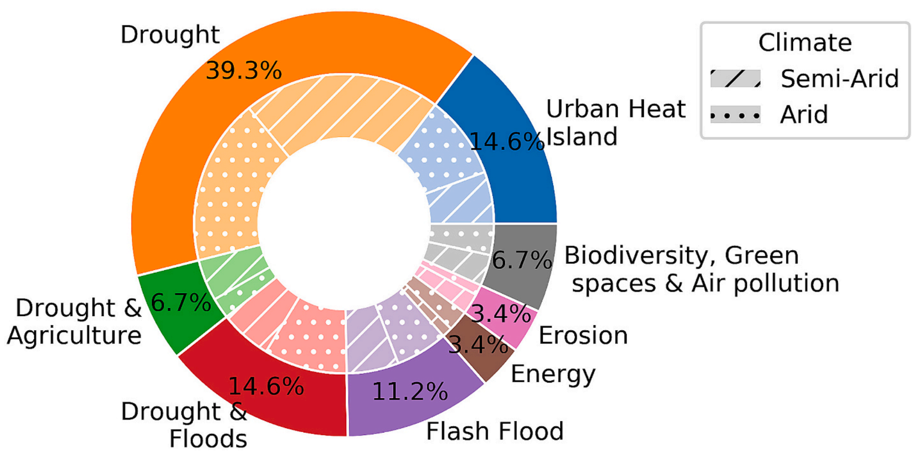

Fig. 3. Main challenges addressed by NbS implementation in arid and semi-arid urban regions.

and maintenance (mediation of waste and flows, maintenance of physical, chemical, and biological conditions), and cultural (physical, intellectual, spiritual, and symbolic interactions with ecosystems and landscapes) (Haines-Young and Potschin-Young, 2018). This classification provides a structured basis for integrating ecosystem service assessments into NbS implementation (Marchioni et al., 2025). In this regard, the IUCN Global Standard for Nature-Based Solutions states that NbS must "equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits" (Andrade et al., 2020), reinforcing the essential role of ecosystem services in defining and evaluating the effectiveness of NbS.

Fig. 4 illustrates the range of NbS applied to drought mitigation. Green roofs emerge as the dominant measure (34% of cases), reflecting their effectiveness in retaining moisture, reducing heat stress, and regulating humidity through evapotranspiration. Water storage within the soil reduces runoff and peak discharge during intense rainfall events, thereby mitigating flood risk, while retaining water during dry periods and enhancing drought resilience. Rain gardens account for 18%, demonstrating their role in alleviating urban water scarcity. Other measures include urban parks (10%), detention tanks (8%), and vertical greening (8%), complemented by afforestation and ecological restoration, which emphasize the long-term importance of ecosystem recovery for drought resilience.

For flash flood management, rain gardens again feature prominently, owing to their ability to enhance infiltration in soils that have low water retention capacity after prolonged droughts. Detention tanks (22%) are also widely adopted, as they provide temporary storage of stormwater, while green roofs (22%) contribute by improving retention and permeability despite their limited spatial extent.

Notably, many NbS initiatives address both drought and flood risks simultaneously. Among these, green roofs are present in 40% of cases, underscoring their multifunctional benefits in expanding urban green cover, regulating hydrological cycles, and moderating climatic extremes. Detention tanks (20%) and rain gardens (20%) are frequently implemented alongside green roofs, creating synergistic solutions. By combining storage, infiltration, and evapotranspiration functions, these measures collectively enhance the capacity of cities in arid and semi-arid regions to cope with environmental challenges.

3.5. Vegetation selection

To reach high levels of performance and efficiency, the vegetation choice in the NbS design is a crucial aspect. Given the extensive literature on NbS in Anglo-Saxon contexts, there is a high risk of replicating these approaches, particularly the choice of vegetation, without adapting them to local conditions. In arid and semiarid regions, characterized by extreme climatic conditions, such as high temperatures, drought and low precipitation, and poor soil properties, NbS vegetation selection should be carefully addressed. Vegetation selection should prioritize native species that can thrive in harsh environments with limited water essential. Tailoring NbS to the local environment, considering the water limitations and high temperatures, is crucial for their success: suitable plant selection not only helps to improve the local environment but also enhances the sustainability and long-term benefits of NbS projects.

Among the investigated works, plant selection was specifically characterized and described in 46 out of 70 cases having vegetation, highlighting the importance of this aspect in the NbS application. Among these, 15 reference cases emphasized the use of local vegetation species, primarily to better adapt to local ecological conditions: these native species have evolved over time and have acquired the ability to adapt to specific environmental conditions such as local climate, soil, and water availability. As a result, they tend to exhibit greater resilience and survival in the face of extreme weather conditions like droughts or floods. In addition, as part of

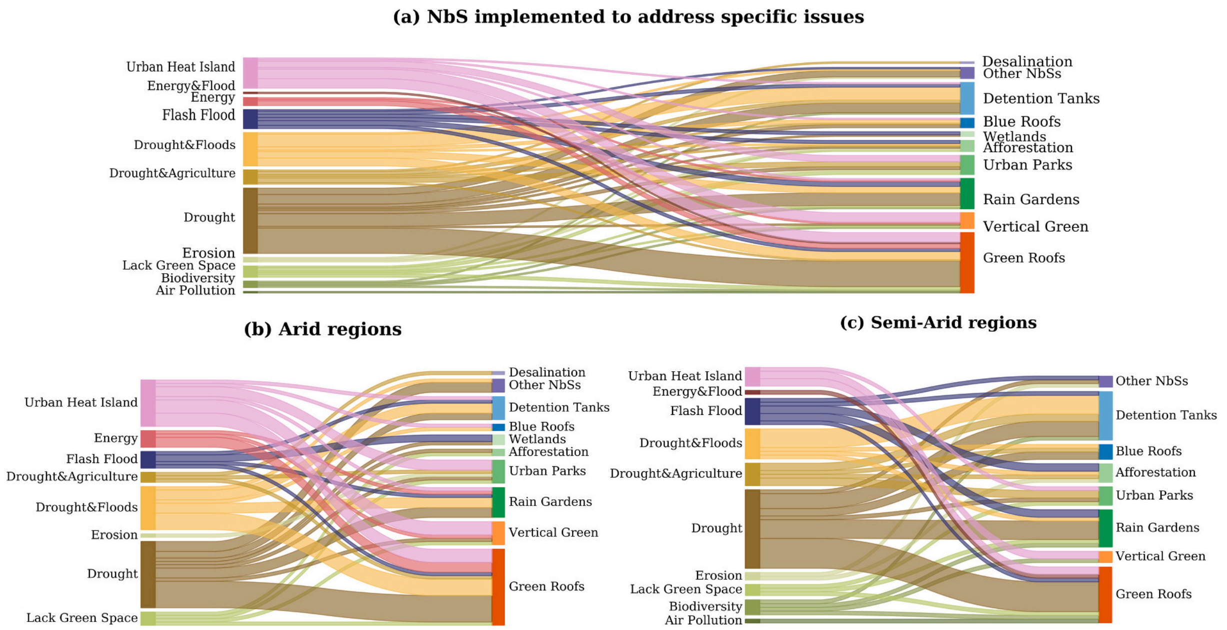

Fig. 4. Issues addressed by the analyzed NbS that can be linked to specific ecosystem services.

the local ecosystem, native species have stable ecological relationships with other plants and animals and can help maintain ecological balance. In contrast, using non-native species poses the risk of introducing invasive species, which can disrupt the existing ecosystem and threaten native biodiversity. In both regions, vegetation selection is mostly discussed for green roofs, rain gardens, vertical green, urban parks, wetlands, and afforestation.

As illustrated in Fig. 5, for each NbS, the vegetation choice can be quite flexible. In the graphs, the selected plants for different NbSs are grouped for arid (Fig. 5a) and semiarid (Fig. 5b) areas, based on the vegetation type. The majority of the works that include plant selection focuses on arid areas, where the choice is more critical. In these regions, for all NbSs, the selection is most commonly oriented toward succulent and drought-resistant plants, highlighted in Fig. 5 with red edges. This choice underlines the importance of selecting vegetation that can easily adapt to the arid climate and environment, surviving and well-performing in water scarcity conditions.

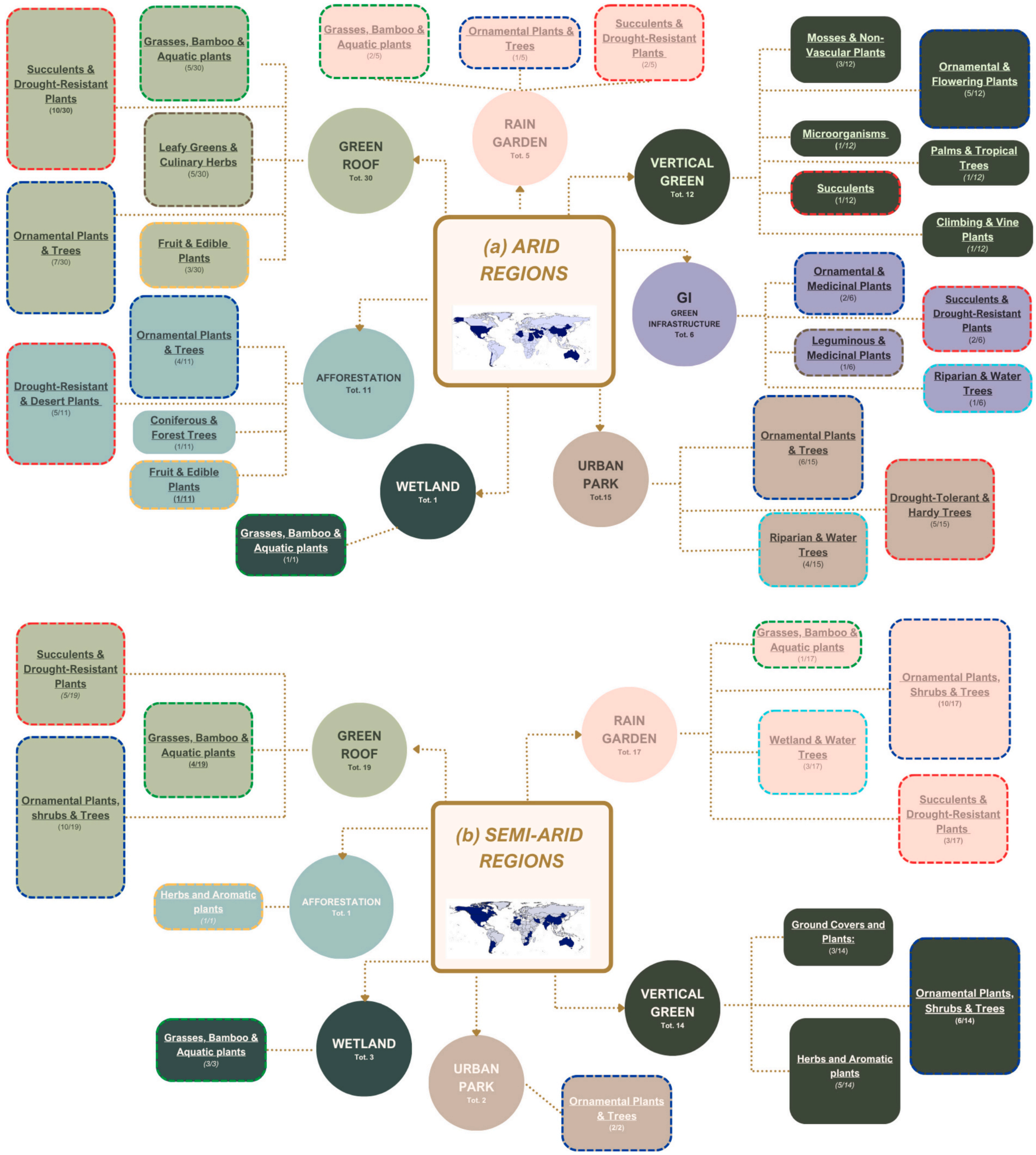

Fig. 5. Classification of the vegetation types per different NbS in arid (a) and semi-arid (b) regions.

Secondly, ornamental plants and trees are commonly installed, showing the importance that it is given to the aesthetic value of the presented NbS. In semi-arid regions (Fig. 5b), the frequency of ornamental plants and trees prevails over the succulent and drought resistant vegetation, probably thanks to the milder climatic conditions and higher mean annual precipitation.

3.6. NbS and water management

This review focuses on urban areas, their challenges, and the most adaptable techniques, not only for addressing specific benefits but also for ensuring successful implementation in water-scarce scenarios. Consequently, the discussion on irrigation is paramount. In these regions, water is a precious and scarce resource, with priority given to drinking water and other essential human activities. Although irrigation is vital for vegetation survival in stressful environments, it cannot be a top priority for resource allocation. Therefore, it is essential to adopt water-saving irrigation techniques and explore alternative water sources as critical solutions.

From the total number of papers reviewed, 88 mentioned the use of an irrigation system. Among these, when the water source was specified, 56 studies referred to rainwater, 11 to greywater, and 2 to desalinated water. Rainwater, being scarce in arid and semi-arid regions, is not a reliable source and would most likely need to be integrated with another supply; therefore, the inclusion of greywater represents a positive approach. Two studies mentioned desalinated water, which is currently an important source in such regions, but entails high economic and environmental costs. An interesting approach, not mentioned in the reviewed studies, is the use of treated sewage effluent (TSE) within a municipal supply network, as implemented, for instance, in the Kingdom of Saudi Arabia (Dawoud et al., 2022). This strategy addresses the issue of the final disposal of treated water—which is often discharged into wadis with negative environmental impacts—while allowing its use for non-contact irrigation with multiple advantages.

4. Discussion

Across the 35 countries in which nature-based solutions have been documented, socioeconomic contexts vary widely. The median national gross domestic product (GDP) is approximately 0.9 trillion USD, yet individual economies range from just over 6 billion USD in Namibia to almost 17 trillion USD in the United States (Our World in Data, 2024). Population density shows an equally wide dispersion, from sparsely populated contexts such as Chañaral (around 1.3 inhabitants/km^2) to highly dense settings/places such as Cairo (approximately 19,129 inhabitants/km^2), with a median of about 75 inhabitants/km^2 (Our World in Data, 2024). The geographical pattern of reported NbS highlights a clear concentration along the arid and semiarid corridor that spreads/goes from the Mediterranean through North Africa and the Middle East, into Central and South Asia, with little representation in the interior of Africa or other remote drylands. This spatial clustering suggests that research and implementation have so far been prioritized in urbanized contexts within this climatic belt. Therefore, the current geographical distribution of NbS is biased toward upper-middle-income and high-income regions, which can more easily absorb these expenses, even though the climate resilience and biodiversity benefits of NbS are globally applicable.

Human activities have progressively disconnected from natural processes, particularly in urban environments where even green areas are often artificial (Izquierdo et al., 2025). In this context, NbS represent a valuable approach, as they seek to restore balance by incorporating functions inspired by ecosystems' multiple services (Seddon et al., 2020; Sowińska-Świerkosz and García, 2022). In arid and semi-arid regions, traditional water management systems, which often can be considered as precursors of modern NbS strategies, played a decisive role in ensuring the survival of local communities. These included cisterns for rainwater collection, underground galleries such as qanats, foggaras, khettaras, or aflaj to tap subsurface flows, shallow wells, and diversion structures to intercept wadi contributions and mountain runoff. By integrating these methods, communities created humid micro-zones suitable for agriculture and sustained more resilient ecosystems. Their efficiency relied on gravity flow, minimization of evaporation losses, and careful collective governance of distribution, which maintained a long-term balance between water supply and demand. Low costs and limited maintenance requirements further supported their success in such challenging environments.

Despite their historical relevance, these systems were progressively abandoned with the advent of modern technologies, including deep boreholes, motorized pumping, and desalination. While these methods provided immediate and seemingly abundant water, they also triggered overexploitation of aquifers, declining water tables, soil salinization, and the weakening of traditional institutions that regulated access and rights. In some contexts, large reservoirs and dams further disrupt subsurface flows and accelerated evaporation, undermining the ecological balance of oasis environments.

Recent research has highlighted the hydrogeological sophistication of traditional oasis systems. Drainage galleries were frequently excavated into permeable formations near mountain foothills, capturing infiltrated rainwater and microflows while reducing evaporation through underground conveyance (Nasiri and Mafakheri, 2015). Flash floods and seasonal overland flows in wadies not only provided episodic surface water but also contributed significantly to groundwater recharge, often enhanced by underground dykes and sediment-retention structures (Ben Hassen et al., 2025). Even condensation processes, facilitated by vertical shafts and subterranean chambers, contributed measurable volumes to the water balance (Nasiri and Mafakheri, 2015). These practices demonstrate a high level of adaptation to extreme environments, achieved with minimal energy input and reduced environmental disturbance (Bainbridge, 2026).

In the context of climate change, where energy consumption and the carbon intensity of water supply are major concerns, there is renewed recognition of the relevance of these heritage practices (Bahraseman et al., 2024). Their reliance on natural processes, passive hydraulics, and local governance closely aligns with the principles of NbS, which integrate ecological functionality with human needs in a sustainable manner. Revisiting and, where appropriate, re-adapting these systems can offer low-impact, resilient strategies for water management in regions where modern solutions may prove unsustainable in the long term.

In arid regions, several NbS are particularly relevant. Examples include green roofs for building cooling, vegetative barriers to reduce sandstorms and highway noise, and rain gardens, trenches, or swales for stormwater management and passive irrigation. These interventions must address challenges typical of arid climates, such as high temperatures, prolonged droughts, sand accumulation, and soil salinity—issues that can be mitigated primarily through careful vegetation selection (Hassani et al., 2021; Naorem et al., 2023).

As highlighted in numerous studies and supported by our results, local territorial characteristics are crucial in NbS design. Unlike technical solutions, which can often be applied with limited sensitivity to site-specific conditions, NbS are inherently embedded in their local context. In regions with limited prior experience, pilot projects are therefore essential (Abeyrathna et al., 2025). They allow for site-specific adaptation, foster stakeholder trust, and provide practical evidence of NbS effectiveness, and our review works in the direction of identifying the strategies most implemented in the different contexts (Abeyrathna et al., 2025). Successful pathways frequently involve partnerships between public stakeholders and research institutions to implement full-scale demonstrators that can be monitored, visited, and experienced. This not only generates robust datasets but also helps reduce opposition to NbS in larger projects (Castelo et al., 2023).

The evaluation of ecosystem services plays a central role in this process. By quantifying benefits through key performance indicators (KPIs), such assessments provide robust, evidence-based information to support guidelines, policies, and incentives. Ultimately, this approach facilitates the broader adoption of NbS at the local scale, ensuring that interventions are both scientifically grounded and socially accepted (Droogers et al., 2012).

Still, economic and institutional limitations may significantly constrain the adaptation of NbS in arid and semiarid regions. The implementation of NbS often requires substantial upfront investment in infrastructure, capacity building, and long-term maintenance, which can be challenging where public budgets are limited and farmers or local communities lack access to credit and financial instruments. Moreover, the economic benefits of NbS, such as improved groundwater recharge, soil fertility enhancement, or reduction of flood risks, tend to materialize over the medium to long term, while decision-makers and land users often operate under short-term financial pressures.

From an institutional perspective, NbS adoption can be hindered by fragmented governance, overlapping responsibilities among water, agriculture, and environmental authorities, and the absence of clear regulatory frameworks that recognize NbS as legitimate alternatives to conventional "grey" infrastructure. Weak enforcement of land and water policies, coupled with insufficient integration of NbS into existing planning instruments, further scalability limits. In many arid and semiarid contexts, there is also a lack of institutional mechanisms for cross-sectoral coordination, which is critical given that NbS often deliver multiple co-benefits across water, food, and ecosystems.

Addressing these barriers will require not only financial innovation (e.g., blended finance, payment for ecosystem services, public–private partnerships) but also institutional strengthening, governance reforms, and participatory approaches that embed NbS into long-term water and land management strategies. Our findings indicate that systematic assessment of past and ongoing NbS initiatives—including climatic patterns, the solutions implemented, the type of vegetation and structural measures employed, and their intended objectives—can provide valuable evidence to guide decision-makers. Such evaluations help identify the most effective NbS for specific purposes (e.g., groundwater recharge, soil erosion control, microclimate regulation), thereby supporting context-appropriate selection and reducing the risk of mismatches between ecological potential, socio-economic conditions, and policy goals.

5. Conclusions

Nature-based Solutions (NbS) represent a promising pathway to address the complex challenges of arid and semi-arid regions, as evidenced by the 89 studies analyzed in this review. By restoring ecosystems, enhancing water and soil management, and integrating resource-efficient infrastructure, NbS demonstrate substantial environmental, social, and economic co-benefits across a wide range of dryland contexts. Beyond increasing resilience to droughts, floods, and heat extremes, the reviewed literature highlights their contribution to broader sustainability objectives, including climate change mitigation, biodiversity conservation, and sustainable development.

The analysis shows that NbS are particularly critical in low-income arid and semi-arid countries, where water and food security are under severe stress and population growth rates are among the highest globally. According to the reviewed studies, NbS are consistently associated with improved resource efficiency, livelihood security, and agricultural productivity, although their performance strongly depends on local environmental and institutional conditions. In many cases, their effectiveness is enhanced when combined with adequate governance structures, capacity building, and long-term investment strategies.

As evidenced in the reviewed literature, increasing climate variability, resource scarcity, and rapid demographic change are expected to further enhance the relevance of NbS in dryland regions. The synthesis indicates that their full potential can only be achieved through tailored design adapted to local climatic, geomorphological, and socio-economic conditions, together with stronger policy integration and interdisciplinary knowledge exchange. Embedding NbS into planning and governance frameworks emerges as a key requirement to foster more resilient, inclusive, and sustainable futures for some of the world's most vulnerable environments.

CRediT authorship contribution statement

Davide Danilo Chiarelli: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Mariana Marchioni:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Francesca Padoan:** Writing – review & editing, Writing – original draft, Data curation. **Elena Cristiano:** Writing – review & editing, Writing – original draft, Visualization, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2026.103060.

Data availability

Data will be made available on request.

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