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Evaluating the Effectiveness of Nature-Based Solutions: Technical, Economic, and Managerial Insights from Case Studies Comparisons

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Abstract

In recent years, Nature-Based Solutions (NBS), defined as interventions inspired by ecosystem processes and aimed at generating environmental, social, and economic benefits, have taken on a central role in urban regeneration and climate change adaptation processes. Despite widespread recognition of their advantages, the spread of NBS is still limited by uncertainties related to performance over time, management costs, and governance models. With the intent of overcoming this limitation, this paper proposes a comparative analysis of case studies of green infrastructure in urban areas, with the aim of identifying the main factors that determine their effectiveness and sustainability throughout their entire life cycle. The research, conducted through a critical review of the literature and the application of a SWOT analysis, highlights the technical, economic, and management conditions that influence the performance of NBS in relation to different contexts of application. The outcome of the study is the definition of an interpretative framework to support designers and decision-makers, geared towards the replicability of solutions, the optimization of resources, and the structural integration of NBS into urban and environmental planning and regeneration processes.

Keywords: Nature-Based Solutions (NBS); urban regeneration; climate change adaptation; SWOT analysis

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1. Introduction

Uncontrolled urbanization, climate change, and pollution, especially widespread pollution, pose challenges for urban and peri-urban ecosystems in addressing their growing vulnerability to environmental risks and anthropogenic impacts [1,2]. In particular, the rapid expansion of urbanized areas, often not supported by adequate planning and management strategies, has led to the progressive fragmentation of ecosystems, the loss of ecosystem services (ESs), and an increase in the exposure of cities to extreme events [3,4]. ESs represent the fundamental contributions of natural ecosystems to human well-being, categorized into provisioning, regulating, cultural, and supporting services [5]. Their importance is paramount, as they underpin global economic stability, food security, and public health through processes such as carbon sequestration, water filtration, and pollination. Essentially, ESs provide the biophysical foundation upon which modern civilization depends for resilience and sustainability. However, the functional integrity of these systems is

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currently facing existential risks. The most significant threats include rapid, anthropogenically driven climate change, which destabilizes ecological cycles, and widespread pollution resulting from intensive urbanization and land-use intensification, which degrades the inherent capacity of ecosystems to regenerate [6,7].

In recent years, there has been a significant increase in key climate indicators: according to the latest reports from the World Meteorological Organisation (WMO), atmospheric concentrations of CO_2 have reached unprecedented levels, and global temperatures have risen by more than +1.3 °C compared to pre-industrial levels. At the same time, the global average sea level has risen by more than 25 cm, highlighting an acceleration in global warming processes and confirming the systemic and irreversible nature of many impacts associated with climate change [8]. These trends reinforce the urgency of adopting effective mitigation and adaptation strategies, particularly in urban contexts, where population, infrastructure, and vulnerability are concentrated. These trends confirm the acceleration of climate change and the need for urgent action.

The increasing pollution is equally worrying and concerns the contamination of the environment from sources that cannot be localized but are widespread throughout the territory [9,10]. In contrast to point sources, which are easily identifiable and localisable, diffuse pollution derives from a multitude of sources distributed throughout the territory and is often associated with human activities such as intensive agricultural practices, industrialization, vehicular traffic, soil impermeabilization, and unsustainable use of resources. This type of pollution, also known as "diffuse" or "non-point source" pollution, can affect the air, water, and soil, and its causes are many, often linked to human activities [11]. At the ministerial level, the complexity of the phenomenon has led to the establishment of dedicated technical and legal working groups aimed at defining integrated approaches to analysis, regulation, and intervention. However, the persistence of these critical issues highlights the need for systemic and innovative solutions capable of acting simultaneously on multiple environmental, climatic, and social dimensions.

In this context, Nature-based Solutions (NBS) represent innovative strategies capable of addressing environmental challenges in an integrated approach. In particular, NBS have gradually established themselves in scientific debate and European policies as an integrated approach capable of jointly addressing the challenges posed by climate change, biodiversity loss, and the degradation of urban ecosystems [12]. The concept of NBS is not new: almost equivalent terminology, such as "ecosystem-based approaches", has been around for decades [13]. However, since the beginning of the century, policymakers have begun to focus on their potential to deliver tangible benefits and build resilience to climate change risks. The concept, understood as a nature-based response to climate issues, emerged in the early 2000s. It was initially supported by the International Union for Conservation of Nature (IUCN), which describes NBS as actions that protect, sustainably manage and restore natural or modified ecosystems, while providing benefits for human wellbeing and biodiversity [14], and subsequently by the European Commission (EC), which recognizes NBS as nature-inspired and nature-based solutions that are cost-effective and can deliver environmental, social and economic benefits, while helping to strengthen resilience [15]. These solutions are based on restoring or imitating ecological processes and aim to re-establish the relationship between anthropogenic and natural systems through multifunctional and adaptive interventions.

NBS include a heterogeneous set of interventions which, while sharing a reference to ecosystem processes, differ in terms of territorial scope, scale of application, and prevailing functions. The catalogue of solutions currently available shows how NBS can be organized into four macro-domains: water management, forest systems, agro-ecosystems, urban and peri-urban areas, and coastal and marine [13,16]. There is below a summary and description of the main types of NBS, in relation to the categories identified [16], showing their scale of application, benefits, and the climate impacts they address (Table 1).

Table 1. Structured summary of nature-based solutions according to scale of intervention, type, benefits, and climate impact.

Topographical Area	NBS Typology	Scale of Application	NBS Benefits	Climate Impact Addressed	Source
Water management	Floodplain restoration, canal renaturalization, riparian strips	Medium–Extra Large	Flow regulation, flood reduction, groundwater recharge, and water quality	Floods, Droughts	[17]
Forest systems	Forest protection and restoration, sustainable forest management, and integration of hotels into the landscape	Large	Carbon sequestration, slope stability, and biodiversity	Fires, Floods, Heat stress	[18]
Agro-ecosystems	Agroforestry, improving soil and water management	Small–Medium	Retention of water and soil, mitigation of heat stress, control of disease and pests, and carbon sequestration	Floods, Heat stress, Droughts	[19]
Urban and peri-urban areas	Green roofs and walls, permeable pavements, rain gardens, bioswales, urban wetlands	Small–Medium	Carbon sequestration, human health and well-being, cooling air temperature, and biodiversity	Environmental pollution, heat stress, and floods	[20]
Coastal & Marine	Dune, living shorelines, and seagrass	Large–Extra large	Erosion protection, habitat quality	Sea level rise, Floods	[21]

Numerous studies have demonstrated how NBS can provide a variety of ecosystem services: urban heat island mitigation, hydraulic risk reduction, carbon sequestration, improved air quality, and increased psycho-physical well-being of the population [22–24]. However, despite the broad consensus on the potential benefits, their spread on different scales is still limited and uneven [25]. Indeed, application experiences highlight recurring critical issues related to the difficulty of predicting performance over time, the lack of sustainable economic models, the fragmentation between stakeholders, and the lack of shared operational protocols [26,27].

Many contributions focus on assessing the environmental benefits of NBS, while the technical-constructive, economic-financial, and managerial aspects that determine their effectiveness throughout the entire life cycle are less in-depth. In particular, the following relative uncertainties remain:

- To choose the most appropriate solutions based on the climatic and morphological contexts;
- To construction and maintenance costs and related financing mechanisms;
- To the governance and management models necessary to ensure their durability.

Considering the critical issues that have emerged, this paper aims to explore the advantages and critical issues of certain categories of Nature-Based Solutions applied in urban areas, through a joint analysis of the factors that influence their implementation. To this end, the SWOT methodology is adopted as a useful tool for identifying the strengths, weaknesses, opportunities, and threats of the various solutions, considering not only environmental aspects but also technical, economic, and managerial dimensions.

The utility of the SWOT methodology lies in its ability to synthesize these disparate elements into a coherent strategy. By cross-referencing helpful factors with harmful ones, decision-makers can formulate "SO" (Strength-Opportunity) strategies to maximize potential, or "WT" (Weakness-Threat) strategies to minimize risk exposure. In the context of complex interventions like Nature-Based Solutions, this methodology provides a structured approach to navigate technical and economic uncertainties, ensuring that selected strategies are both resilient and contextually appropriate.

In the field of environmental management, SWOT analysis has been progressively adapted to include the perspective of ecosystem services, allowing for the joint assessment of the ecological and social dimensions of territorial interventions. The ecosystem approach allows strengths and weaknesses to be interpreted in relation to the capacity of ecosystems to provide benefits to the population, while opportunities and threats are linked to processes of land use change, urbanization, and climate pressures [28].

The application of SWOT analysis to NBS allows for the evaluation not only of environmental performance, but also of the technical, economic, and management conditions that determine their long-term success. Several studies [29–31] show that SWOT, integrated with ecosystem service indicators and stakeholder involvement, allows for the identification of barriers to implementation, co-benefits, and trade-offs between ecological functions and urban development objectives.

In this paper, SWOT analysis is used as a methodological tool to examine the main types of NBS (with particular reference to urban forests and green roofs) in a comparative analysis throughout the entire project cycle, from the planning phase to post-operational management.

The intent is to provide a knowledge framework that can support planners and decision-makers, contributing to a more informed choice of NBSs according to different application contexts and operating conditions. In this perspective, green infrastructure is considered as part of evolving urban regeneration processes, whose success depends on the balance between expected performance, available resources, and management methods over time.

Rather than proposing new NBS technologies, this study aims to contribute to the operational understanding of their implementation in urban contexts. The novelty of the research lies in the integration of a comparative analysis of case studies with an evaluation framework based on SWOT analysis that simultaneously considers technical, economic and managerial dimensions. This approach allows for the identification of critical factors that influence the effectiveness of urban NBS and provides practical insights to support planning and decision-making processes.

2. Materials and Methods

This article is structured as a development of a methodological framework based on a comparative synthesis of case studies. Specifically, it uses SWOT analysis as a diagnostic tool to bridge the gap between theoretical ecosystem services and practical urban management.

Integrating technical, economic, and management dimensions, this methodology identifies the practical conditions for NBS implementability and sustainability. Moving beyond documented environmental benefits, the study establishes an operational framework to support planners in the structural integration and deployment of these solutions.

2.1. Research Strategy

Specifically, the research focused on in-depth case studies, identified through a targeted review of scientific literature and technical-operational documentation. The research was conducted between November 2025 and January 2026 on the main databases (Scopus, Web of Science, Google Scholar) and on European institutional portals dedicated to NBS. In order to ensure transparency and replicability, a Boolean search string has been defined, built around three main themes: NBS concept, relevance to climate change, assessment of benefits, and management aspects. The string used is as follows: ("nature-based solutions" OR "NBS" OR "ecosystem-based adaptation" OR "urban ecosystem services" OR "urban biodiversity") AND ("benefits" OR "performance" OR "costs" OR "management" OR "governance"). Searches were applied to the title, abstract, and keyword fields when supported by the database.

According to the overview defined in Section 1, which highlighted the growing vulnerability of ecosystems to uncontrolled urbanization, climate change, and widespread pollution, it was decided to concentrate the analysis on NBS case studies applied in urban areas.

This observation is supported by the results of the quantitative review by Fang et al. [32], in which 142 case studies, published between 2016 and 2022, were examined, highlighting how NBS are mainly used for urban flooding and heat stress management. The most frequently adopted types are green roofs and urban forests, followed by permeable pavements, rain gardens, and multifunctional parks. The same study shows that most research focuses on the potential capacity of NBS to provide ecosystem services, while aspects related to actual service flows and social demand are less explored [32].

This evidence motivated the decision to focus this study on urban case studies, an area in which the literature recognizes greater maturity in application and a clearer relationship between the solutions adopted and measurable benefits. Furthermore, the still limited attention paid to management and monitoring aspects confirms the need for an analysis that considers not only environmental performance but also the technical and economic factors that influence its effective implementation.

2.2. Focus on Case Studies

Based on the typological classification presented above and the evidence emerging from the literature, the analysis of the case studies was limited to the categories of NBS considered most representative for urban contexts, in particular, urban forestry and green roofs. This choice reflects the desire to focus on widely used solutions, characterized by well-established technical literature and a direct impact on key urban issues, such as heat island mitigation, stormwater management, and environmental quality improvement.

For each of these categories, the development process was examined, divided into the following phases: preliminary analysis of the context, definition of performance objectives, choice of technical solutions, economic evaluation, management methods, and monitoring. Then, the information collected was used for comparative analysis through the application of SWOT analysis, a tool that allows for the systematic organization of the strengths, weaknesses, opportunities, and threats of the various solutions, promoting an integrated and transparent assessment.

2.3. SWOT Analysis

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) is one of the most widely used tools in strategic planning and decision support, as it allows internal and external factors that influence the effectiveness of an intervention or policy to be integrated into a single interpretative framework [33]. The structure divides these factors into two main categories (Figure 1): strengths and weaknesses, which can be traced back to the intrinsic characteristics of the system analyzed (internal origin), and opportunities and threats, which derive instead from the socio-economic, institutional, and environmental context (external origin) [31].

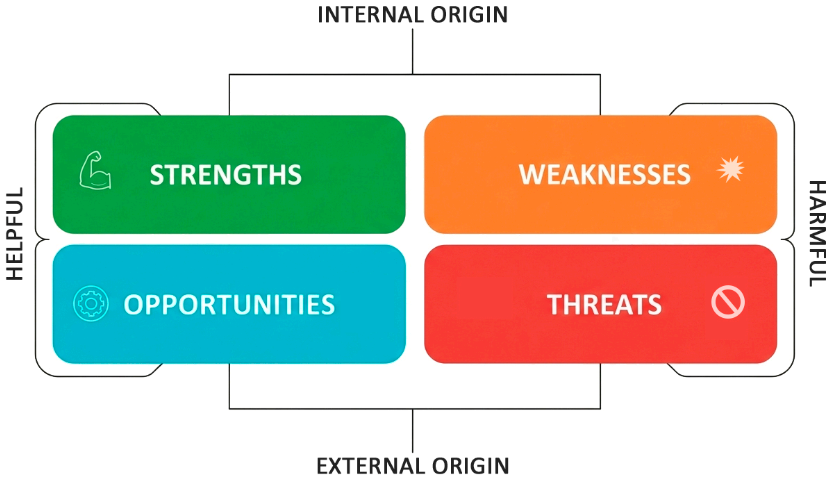

Figure 1. Illustrative diagram of a SWOT matrix.

The SWOT analysis, as illustrated in the provided matrix, serves as a foundational strategic planning methodology designed to evaluate the internal and external environments of a project or organization. This framework systematically categorizes factors into four distinct quadrants based on two primary axes: the origin of the factor (Internal vs. External) and its potential impact (Helpful vs. Harmful). By delineating these dimensions, the methodology enables a comprehensive assessment of the strategic landscape, facilitating the identification of core competencies and critical vulnerabilities.

The material implementation of a SWOT analysis for Nature-Based Solutions (NBS) requires a multidisciplinary framework that integrates ecological performance with socio-economic viability. Practitioners must first identify internal Strengths, such as the delivery of diverse ecosystem services and biodiversity enhancement, while simultaneously addressing Weaknesses like the necessity for long-term maintenance and potential land-use competition. This stage is effectively executed through participatory stakeholder workshops and expert consultations to establish a comprehensive baseline of the project's internal capacities.

The external assessment focuses on Opportunities arising from international climate policies and green financing, contrasted against Threats such as regulatory fragmentation or extreme climatic shifts. Materially, this evaluation is enhanced by utilizing Multi-Criteria Decision Analysis (MCDA) and Geographic Information Systems (GIS) to map spatial vulnerabilities and co-benefits.

Through the systematic identification of strengths, weaknesses, opportunities, and threats for each category, the aim is to construct an evaluation framework to support planners' choices and translate scientific evidence into operational guidelines for decision-making processes.

3. Results

The initial database query produced a document corpus exceeding 250,000 records, highlighting a marked transversality and widespread diffusion of the topics analyzed across multiple research domains. Given the heterogeneity and breadth of the raw dataset, it was necessary to refine the methodology to isolate the most relevant and authoritative contributions. Thus, restrictive inclusion criteria were applied, limiting the selection exclusively to scientific articles published between 2021 and 2026. This chronological and typological delimitation was adopted to ensure that the analysis focused on the most recent state of the art, integrating only the most up-to-date empirical and theoretical evidence in the contemporary academic landscape. The application of restrictive inclusion criteria subsequently narrowed the dataset to approximately 10,200 contributions, ensuring alignment with the most recent technological and methodological developments.

Subsequently, in line with the methodological framework outlined in Section 2, which focused on the application of NBS in urban areas, the field of investigation was further refined by integrating specific semantic descriptors. Specifically, the application of the keywords "urban forestry" and "green roofs" made it possible to significantly narrow down the document sample. The query returned approximately 5660 results for the first search term and approximately 1950 for the second.

Through systematic screening of titles and abstracts, 100 potentially relevant contributions were isolated and subsequently subjected to a full-text eligibility review. From these results, contributions of an exclusively theoretical or systematic review nature, as well as studies without a description of the procedural implementation process or evaluation elements relating to technical-economic and management aspects, were excluded.

In addition to excluding purely theoretical studies and articles lacking procedural implementation, a series of explicit exclusion criteria were applied during the full-text screening phase. Studies were excluded when: (i) they presented only conceptual or regulatory frameworks without reference to implemented case studies; (ii) they referred to non-urban contexts; (iii) they reported environmental performance without providing technical, economic, managerial or governance information; (iv) they lacked sufficient methodological details to allow the extraction of comparable parameters. This refinement allowed us to progressively reduce the sample to a limited number of case studies characterized by adequate completeness of information and comparability.

As mentioned in the previous sections, the choice to focus the analysis on urban case studies is based on the literature highlighting how NBS assume strategic relevance in high-density urban systems, where climatic and environmental pressures are most accentuated [34]. Furthermore, several contributions highlight the need to move beyond the purely performance approach to adopt a processual reading of NBS implementation, capable of integrating planning, governance, and monitoring over time [35].

3.1. Procedural Process for the Implementation of Nature-Based Solutions

The comparative analysis of the case studies allowed us to reconstruct a recurring procedural path in the implementation of urban NBS, in line with the main planning frameworks proposed in the European context [36,37].

In a first phase, a preliminary analysis of the context is conducted, aimed at identifying environmental and climate critical issues (urban heat island, rainwater management, biodiversity deficit) and at establishing the regulatory and planning framework for the intervention [38]. This is followed by a co-design and goal-setting phase, which includes the involvement of local stakeholders and the evaluation of typological alternatives. The literature highlights how the participatory dimension represents a determining factor for the legitimacy and long-term sustainability of interventions [35].

The third phase concerns executive design and multicriteria evaluation, including cost–benefit analyses, ecosystem services estimation, and microclimatic or hydrological modelling. At this stage, significant differences emerge between urban forestry and green roofs, especially in terms of spatial scale, time horizon of effects, and maintenance complexity.

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The practical implementation is accompanied by the definition of management and financial models, which may include public–private partnerships or tax incentives. Finally, a post-operational monitoring phase [39] allows for the assessment of environmental and socio-economic performance over time.

3.2. Case Study Analysis: Urban Forest Initiatives in European Cities

The analysis was subsequently expanded through the selection of three European urban forestry case studies implemented in metropolitan contexts: the Bosque Metropolitano project in Madrid (Spain), the urban forest programme at the Hôtel de Ville in Paris (France), and the Forestami initiative promoted in the city of Milan (Italy).

The first case study concerns the Bosque Metropolitano project, promoted by the Municipality of Madrid with the aim of creating a green belt of approximately 75 km around the city. The project aims to connect existing parks, peri-urban agricultural areas and ecological corridors through urban forestry and renaturalization interventions [40]. According to project estimates, the green infrastructure should contribute to mitigating the urban heat island effect, reducing air pollution and improving metropolitan ecological connectivity [40]. From a technical point of view, the project integrates various types of intervention, including linear planting, forest parks and reforestation areas with native species adapted to the Mediterranean climate. However, the creation of green infrastructure on this scale poses significant challenges in terms of long-term management, water availability and institutional coordination between different administrative levels.

The second case study concerns the urban forest initiative at the Hôtel de Ville in Paris, which is part of the city's broader climate adaptation strategy [41]. The project involves transforming heavily mineralised squares and public spaces into urban ecosystems with high plant density, with the introduction of trees, shrubs and permeable surfaces. The main objective is to increase the climate resilience of the historic centre by reducing surface temperatures, increasing shade and improving urban microclimatic comfort. From a design perspective, the project is an example of high-density urban forestry applied in densely built-up urban contexts, where space is limited and the management of underground infrastructure represents a significant constraint [41,42].

The third case study analyzed is the Forestami programme, one of the most significant European urban reforestation initiatives. The project involves planting around three million trees by 2030 in the Milan metropolitan area, with the aim of increasing tree cover, improving air quality and strengthening the city's climate resilience [43]. Compared to previous cases, Forestami is configured as a multi-level territorial strategy involving public bodies, universities and private actors in the planning and management of new green infrastructure [44]. The project integrates urban forestry interventions, the redevelopment of peri-urban spaces and the creation of ecological corridors, highlighting the role of collaborative governance in the implementation of NBS.

The following table (Table 2) summarizes the technical and economic parameters of the case studies analyzed, highlighting how the initial investment is closely related to the level of ecosystem services expected and the technological complexity of the site.

The analysis of these three case studies highlights how urban forestry strategies can take different forms depending on the territorial scale, climatic conditions and governance models adopted. Despite these differences, some common elements emerge, including the importance of selecting plant species adapted to the local context, the need for long-term management and maintenance strategies, and the central role of integrated green infrastructure planning in urban adaptation to climate change processes.

Table 2. Urban forestry: technical and economic parameters of the case studies analyzed.

Case Study	City Location	Surface	Implementation Costs	System Costs	Reference
El Bosque Metropolitano	Madrid	∼600 hectare	∼25–40 €/m^2	∼1.50–2.50 €/m^2 per year for the first 5 years (critical stage of engraftment)	[40]
Place Hotel de Ville	Paris	0.25 hectares that are part of the programme to create 300 hectares of new green spaces by 2030.	∼45–60 €/m^2	∼3.00 €/m^2 per year	[41,42]
Forestami	Milan	700 hectare	∼20–30 €/m^2	∼2.00 €/m^2 for the first few years (mainly for relief irrigation and mowing)	[43,44]

3.3. Case Study Analysis: Green Roofs in European Cities

In line with the analysis conducted for urban forestry interventions, a selection of representative case studies in European urban contexts was also developed for the green roofs category. The aim was to analyze examples characterized by different design and management approaches in order to highlight the main technical variables that influence the environmental performance of green roofs. In particular, the analysis considered three significant experiences: an experimental multilayer system installed in Palermo (Italy), widespread green roof implementation policies in the city of Copenhagen (Denmark) and RESILIO project—Resilience Network of Smart Innovative Climate-adaptive Rooftops developed in the city of Amsterdam (Netherlands).

The first case study concerns the experimental installation of a multilayer green roof in Palermo, analyzed in a recently published study on its thermal effectiveness in the Mediterranean climate [45]. The system consists of an advanced stratigraphy composed of substrates of different grain sizes, drainage layers and vegetation selected for its resistance to the water and heat stress conditions typical of hot climates. The experimental results show a significant reduction in surface temperatures and an improvement in the energy performance of the building below, confirming the potential of green roofs as a technology for mitigating urban heat islands in Mediterranean contexts [46].

A second significant example is the city of Copenhagen, which in 2010 introduced one of Europe's most advanced urban policies for the spread of green roofs [47]. The municipal plan requires the installation of green roofs on all new buildings with flat roofs above a certain size, as part of the urban strategy for climate change adaptation and sustainable rainwater management. Thanks to this regulatory approach, the city has seen rapid growth in the area of green roofs, with hundreds of buildings equipped with extensive systems that contribute to reducing urban runoff and improving the urban microclimate [48].

The third case study concerns the RESILIO project, developed in the city of Amsterdam and completed in 2022 [49]. The project involved the installation of a network of smart blue-green roofs on residential and public buildings, integrating plant systems with rainwater storage and dynamic management systems [50]. The roofs are equipped with sensors and digital control systems that allow the level of water stored in the substrate to be adjusted according to weather forecasts, increasing retention capacity during heavy rainfall and promoting evapotranspiration during hot periods. These systems represent an evolution of traditional green roofs, as they integrate hydraulic infrastructure, digital technologies and urban vegetation into a single adaptive system [50].

From an environmental performance perspective, the blue-green roofs of the RESILIO project have demonstrated a significant capacity to retain rainwater and reduce peak runoff, contributing to the management of intense rainfall and the mitigation of the effects of climate change in densely built-up urban areas.

The comparative analysis shown in the table (Table 3) below shows that the costs of implementing green roofs can vary depending on the type of intervention, the scale of application and the technologies used. In particular, construction costs range from approximately €80 to €220 per square metre, with lower values for large-scale extensive systems and higher costs for more technologically complex systems, such as blue-green roofs, which integrate water management and storage systems.

Table 3. Green roofs: Urban forestry: technical and economic parameters of the case studies analyzed.

Case Study	City Location	Surface Implementation	Implementation Costs	System Costs	Reference
Green roof multilayer	Palermo	Experimental and building-scale interventions (e.g., university roof gardens or pilot buildings)	~90–140 €/m^2	~1.50–2.50 €/m^2 per year for the first 5 years (critical stage of engraftment)	[45,46]
Green roof policy	Copenhagen	>200,000 m^2 of roofing surveyed	~80–130 €/m^2	~1.5–3 €/m^2 per year	[18,47]
RESILIO project	Amsterdam	~10.000 m^2	~150–220 €/m^2	4–6 €/m^2 for the first few years (mainly for relief irrigation and mowing)	[49]

3.4. Comparative Analysis Between Urban Forests and Green Roofs

The analysis of the selected case studies, supported by comparison with scientific literature, highlights substantial differences between urban forestry and green roof interventions in terms of spatial scale, time horizon of effects, management intensity, and type of ecosystem benefits.

Urban forestry interventions mainly operate on an urban or suburban scale and are characterized by a significant capacity for microclimatic mitigation and water flow regulation. Several studies show that increased tree cover can reduce air temperature by between 1 and 4 °C in densely built-up urban areas, thanks to the combined mechanisms of shading and evapotranspiration [51]. Furthermore, the presence of trees contributes significantly to carbon sequestration and the removal of atmospheric pollutants, with measurable benefits for air quality [52,53]. However, these effects develop gradually and are closely dependent on the maturation time of the vegetation, the species used, and the availability of water. The effectiveness of urban forestry measures is therefore linked to medium- to long-term planning and an appropriate management model.

Green roofs, on the other hand, mainly act on a building or block scale, with more immediate and directly measurable effects on the building envelope. The literature highlights how green roofs can reduce surface runoff by up to 50–80%, depending on the thickness of the substrate and climatic conditions [54], as well as contributing to the reduction in energy requirements for summer cooling through increased thermal inertia and evapotranspiration processes [54]. From a microclimatic point of view, the cooling effect is generally more localized than urban forestry measures, but it is more technically controllable and more easily replicable in high-density building contexts.

From an economic perspective, urban forestry involves relatively low initial costs per planting unit, but entails significant long-term management costs related to irrigation, pruning, phytosanitary monitoring, and replacement of specimens [55]. Furthermore, soil availability is a limiting factor in established contexts. On the other hand, green roofs have higher installation costs (€/m^2), due to the technical layers and structural checks required for the building, but they require more standardized and predictable management over time.

Analysis of the selected contributions shows that both technologies are widely used in Europe, with a particular concentration in Central European countries and the Mediterranean area, where pressures related to the urban heat island effect and rainwater management are particularly significant [56]. In Mediterranean contexts, urban NBS are frequently adopted as climate adaptation tools, especially in response to heat waves and prolonged periods of drought.

Another recurring factor concerns the limited diversification of plant species used. In the case of extensive green roofs, the literature highlights the prevalent use of species of the *Sedum genus*, selected for their resistance to drought and low maintenance requirements [57,58]. Similarly, urban forestry projects often involve the use of a limited number of tree species considered to be resilient and fast-growing, with the risk of reducing biodiversity and increasing vulnerability to biotic and abiotic stress.

While this typological standardization ensures greater technical predictability, it can also limit the adaptive capacity of urban ecosystems in the long term, highlighting the need for design strategies that are more oriented towards diversification and ecological resilience.

3.5. SWOT Analysis Applied to Urban Forest and Green Roof Categories

In line with the methodological framework described in Section 2, it was applied to the two main categories of NBS (urban forests and green roofs) under study in order to systematize the technical, economic, and management factors that influence their effectiveness in urban contexts.

The analysis was developed by integrating evidence from scientific literature, technical documentation, and European guidelines on NBS. The SWOT matrix allows us to distinguish between internal factors (strengths and weaknesses) and external factors (opportunities and threats), providing a useful interpretative tool for decision-making and strategic planning.

3.5.1. SWOT—Urban Forest

As shown in the SWOT analysis (Table 4), from an environmental point of view, urban forests are one of the most effective solutions for mitigating the urban heat island effect thanks to their shading and evapotranspiration processes. They also offer multiple benefits in terms of carbon sequestration, improved air quality, increased biodiversity, and hydrological regulation. Their multifunctional nature is one of their main strengths.

However, the effectiveness of urban forests is highly dependent on soil availability, species selection, soil and climate conditions, and ongoing management over time. The effects take a medium to long time to mature and require strategic planning. Opportunities include integration into building regulations, tax incentives, and urban climate adaptation strategies. Threats are related to regulatory barriers, inadequate maintenance, and extreme climate variations that can compromise their performance.

Table 4. The SWOT analysis of urban forests [15,59,60].

Origin	Helpful	Harmful
	Strengths	Weakness
Internal	High microclimatic mitigation capacity; CO_2 sequestration; improved air quality; increased biodiversity; social and recreational benefits; ecosystem multifunctionality.	Dependence on soil availability; long maturation times; ongoing maintenance costs; sensitivity to water and phytosanitary stresses; multi-level management complexity.
	Opportunities	Threats
External	Integration in climate adaptation plans; access to European funding; regeneration of degraded areas; development of urban ecological corridors; carbon credits and green financing.	Competition for land use; urban pressure; extreme climate change; fragmented management between local authorities; reduction in species diversity.

3.5.2. SWOT—Green Roofs

Table 5 shows the results of the SWOT analysis (Table 5). The main strengths include high replicability in densely built-up areas, reduction in surface runoff of rainwater, improvement of the building's energy performance, and localized mitigation of the urban heat island effect. In addition, green roofs contribute to extending the useful life of waterproofing membranes.

Table 5. SWOT analysis of green roofs [45,61,62].

Origin	Helpful	Harmful
	Strengths	Weakness
Internal	Replicability; runoff reduction; improved energy performance; local UHI mitigation; membrane protection; applicability in high-density areas.	High initial costs; need for structural verification; specialist and periodic maintenance; limited biodiversity in extensive systems; variable performance depending on substrate moisture content.
	Opportunities	Threats
External	integration into building regulations, tax incentives, integration with renewable energy, and urban climate adaptation strategies.	Typological standardization; limited awareness of long-term benefits; insufficient and inadequate maintenance; extreme weather events; failure to adapt to climate conditions.

Weaknesses include initial installation costs, the need for structural checks, dependence on climatic conditions, and the need for specialist and periodic maintenance. Extensive systems have limited plant diversity, with a predominance of drought-resistant species (e.g., *Sedum* spp.), which can reduce ecological complexity.

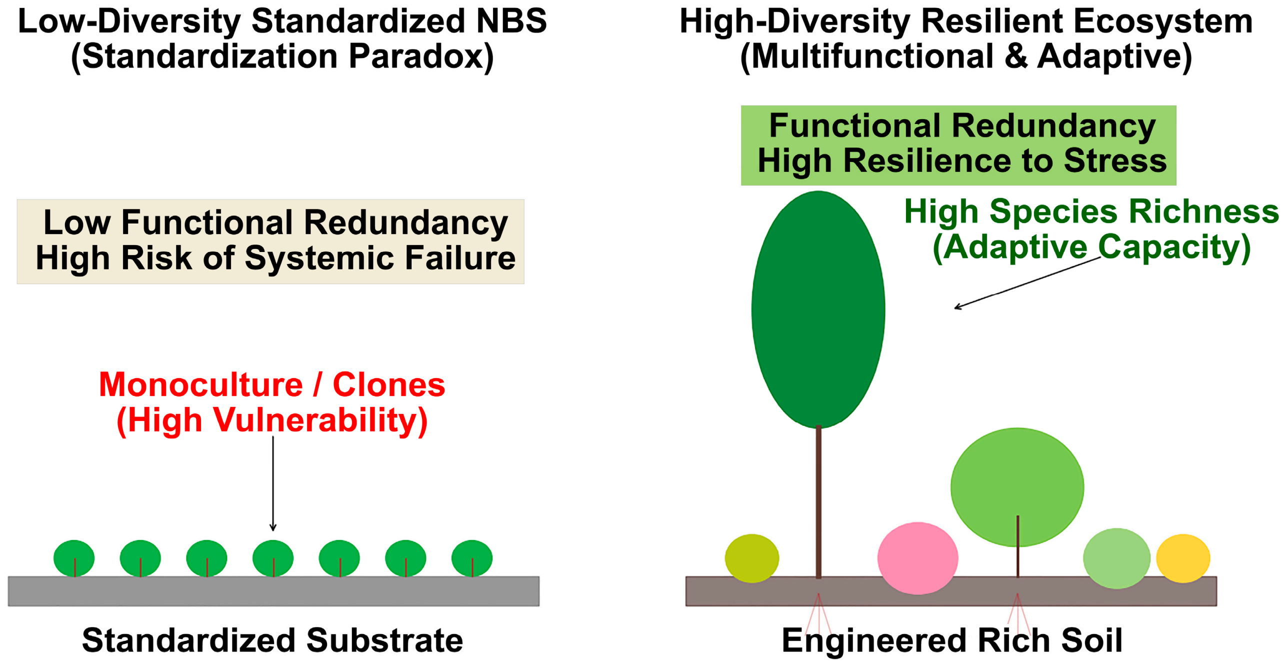
Opportunities include integration into building regulations, tax incentives, integration with renewable energy, and urban climate adaptation strategies. Threats are related to the lack of uniform technical standards, inadequate maintenance, and extreme climate variations that can compromise performance.

4. Discussion

The transition toward resilient urban environments necessitates a profound re-evaluation of how NBS are integrated into the existing fabric of cities. While the abstract benefits of these interventions are well-documented, a critical gap remains between theoretical potential and long-term operational success. One of the most pressing concerns in contemporary NBS implementation is the paradox of standardization. In the pursuit of technical predictability and reduced initial risk, practitioners often default to a limited palette of plant species, such as the ubiquitous *Sedum genus* for green roofs or a narrow selection of resilient tree species for urban forestry [63]. Although this approach simplifies the design phase and ensures a degree of immediate survival, it introduces a significant structural weakness.

From a SWOT perspective, this over-reliance on a few "tried and tested" species transforms what is initially perceived as a strength—predictability—into a long-term threat: ecological vulnerability. Monocultural or low-diversity interventions lack the functional redundancy required to withstand emerging biotic and abiotic stressors, such as new pests or extreme heatwaves, potentially leading to systemic failure of the ecosystem service delivery [64].

Figure 2 compares two opposing approaches to urban green design: left (Standardized NBS) represents the current trend of using limited species and clones (such as the *Sedum genus* for green roofs or single tree species) (Figure 2).



Legend:
- Green Circles (Uniform) represent monocultural plantings or clones with identical genetic vulnerability.
- Multi-coloured/Multi-sized Shapes represent botanical stratification including trees, shrubs, and herbaceous species.
- Downward Arrows: Indicate the degree of adaptive capacity and functional redun-dancy.

Figure 2. Comparative diagram showing the difference between low-diversity standardized NBS and high-diversity resilient ecosystems. The "High-Diversity" model is designed to support a 1–4 °C reduction in air temperature through enhanced evapotranspiration, compared to the "Low-Diversity" model which remains at high risk of systemic failure during extreme heatwaves or pest outbreaks.

This uniformity reduces initial management complexity but creates a fragile system, lacking functional redundancy and at high risk of systemic collapse in the face of new threats; right (Resilient Ecosystem) shows an intervention based on the diversity of species, structures, and functions. Botanical variety and stratification (trees, shrubs, herbaceous species) ensure high adaptive capacity and greater resilience to climate change and pests.

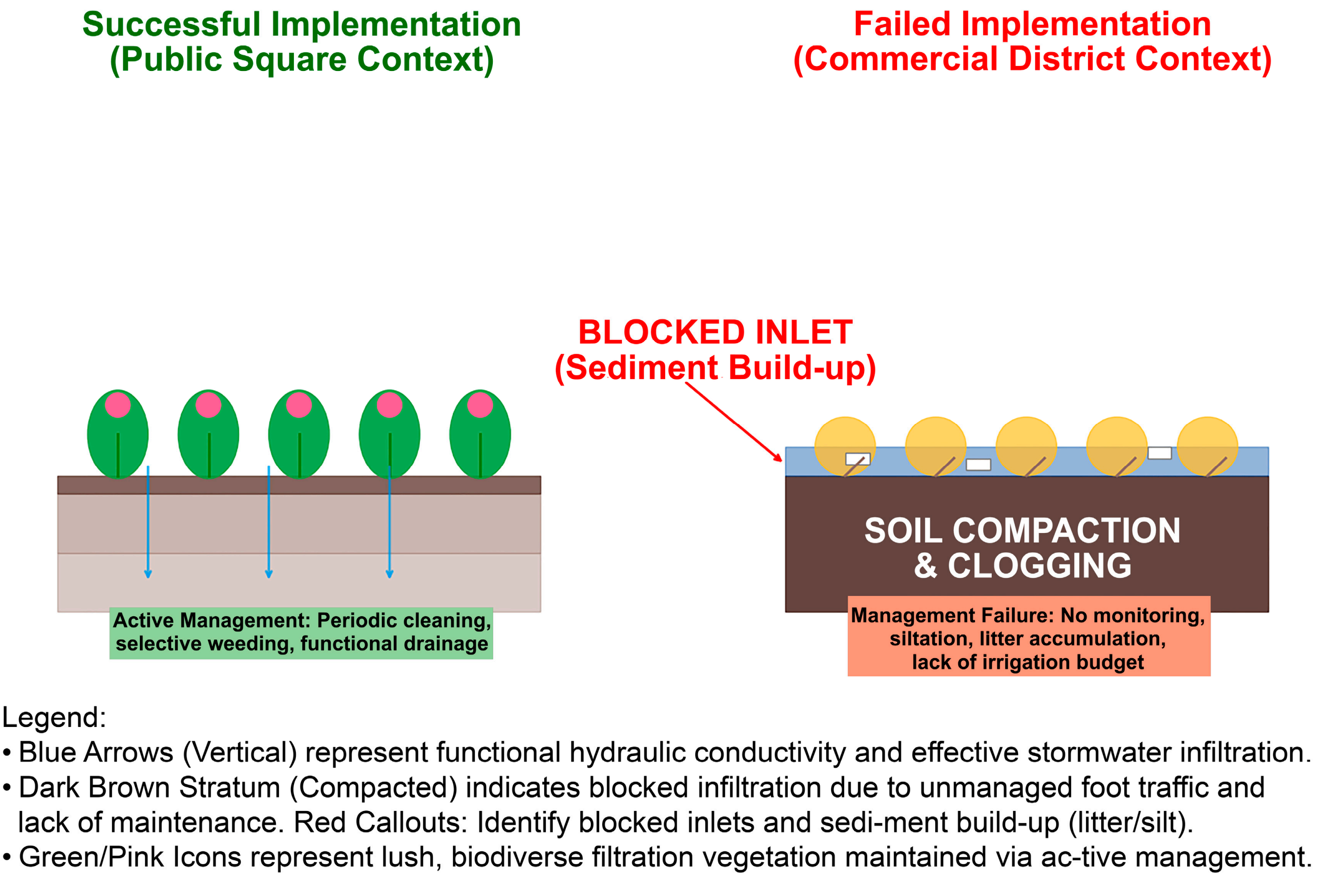
To illustrate the critical role of site-specific governance and management, consider the application of rain garden technology in two similar Mediterranean urban contexts. In the first case, a rain garden implemented within a revitalized public square achieved significant success. The project integrated a dynamic maintenance plan involving local stakeholders and utilized a diverse substrate tailored to local soil permeability, ensuring effective stormwater infiltration during extreme rainfall events. In the second case, an identical rain garden was installed in a nearby commercial district but resulted in failure within two years. The primary cause was a "copy-paste" design approach that ignored local micro-drainage patterns and lacked a post-operational monitoring protocol. The soil became compacted due to unmanaged foot traffic, and the lack of a dedicated maintenance budget led to the death of the filtration vegetation. This comparison underscores that the "technical effectiveness" of an NBS is not an inherent property of the technology itself but a result of the integrated technical, economic, and management conditions under which it operates.

In this perspective, even the assessment of NBS performance requires methodological caution. The evaluation of thermal effectiveness should account for uncertainties associated with infrared surface temperature measurements, particularly in complex urban geometries where radiative exchange, cavity effects, and material emissivity may significantly influence recorded values. Recent simulation-based studies on infrared temperature measurement have demonstrated that radiative transfer mechanisms can introduce systematic deviations if not properly accounted for, especially in semi-enclosed or heterogeneous surfaces [65]. Consequently, the interpretation of surface temperature reductions attributed to green roofs or urban forests should be supported by a rigorous understanding of measurement physics and boundary conditions.

At the same time, emerging data-driven approaches are expanding the analytical capacity to evaluate NBS performance at multiple spatial scales. Machine learning techniques have recently been applied to reconstruct high-resolution air pollution maps from sparse monitoring networks, enabling improved spatial characterization of environmental quality patterns in urban areas [66]. Such approaches may significantly enhance the assessment of ecosystem services delivered by NBS, particularly in relation to air quality mitigation and urban heat regulation. The integration of advanced monitoring methodologies and predictive modelling tools can therefore strengthen evidence-based planning processes, reducing interpretative bias and improving the robustness of performance evaluation.

To further illustrate the operational divergence in NBS performance, comparative Analysis of Technical and Management Success and Failure, Figure 3 presents a side-by-side technical evaluation of rain garden implementation. This image highlights how the same technology can produce opposing results depending on the governance and maintenance context: left (Success), a rain garden in a public square where soil stratification is kept porous, vegetation is lush (biodiversity), and drainage is functional thanks to active management and dedicated funding; right (Failure), the same system in a commercial district, where lack of monitoring has led to soil compaction, debris accumulation (sediment and waste), and blocked water inlet. The vegetation is suffering, turning the NBS into an environmental risk (water stagnation) rather than a service.

The integration of SWOT analysis into the decision-making process offers a path forward by allowing planners to move beyond purely environmental metrics. By cross-referencing internal strengths, such as specialized technical infrastructure, with external threats like economic instability or climate volatility, decision-makers can formulate resilient strategies. Modern research suggests that the future of NBS lies in "multifunctional" and "adaptive" interventions that are structurally integrated into urban planning. This requires shifting the narrative from NBS as isolated "green spots" to NBS as essential urban infrastructure. Ultimately, the transition from successful pilot projects to widespread replicability depends on the creation of operational frameworks that bridge the gap between scientific evidence and the practical constraints of urban management.



Legend:
- Blue Arrows (Vertical) represent functional hydraulic conductivity and effective stormwater infiltration.
- Dark Brown Stratum (Compacted) indicates blocked infiltration due to unmanaged foot traffic and lack of maintenance. Red Callouts: Identify blocked inlets and sedi-ment build-up (litter/silt).
- Green/Pink Icons represent lush, biodiverse filtration vegetation maintained via ac-tive management.

Figure 3. Side-by-side comparison of successful vs. failed rain garden implementation, highlighting soil health and vegetation cover. Successful implementations maintain a runoff reduction capacity of 50–80%, whereas failed implementations transition into environmental risks characterized by water stagnation and loss of filtration service. This integrated visual content clarifies that technical effectiveness is not an inherent property of the NBS itself but is contingent upon the maintenance of porous soil stratification and species richness.

Replicability and Scaling: From Pilot Projects to Systemic Integration

The replicability of NBS serves as a cornerstone of the proposed interpretative framework, aiming to move beyond isolated pilot projects toward systemic urban integration. For these interventions to be successfully transferred across diverse geographical and socio-economic contexts, the framework emphasizes that technical effectiveness must be balanced with economic feasibility and robust management methods. Replicability is not merely a matter of technological "copy-pasting" but requires precise identification of environmental, social, and economic factors that determine performance throughout the entire life cycle. By standardizing these operational conditions within a methodological support tool, planners can optimize resources and ensure that green infrastructure is structurally embedded into environmental regeneration processes. Ultimately, the capacity to scale these interventions depends on overcoming current uncertainties regarding governance models and maintenance costs, converting theoretical ecosystem benefits into tangible, resilient urban assets (Table 6).

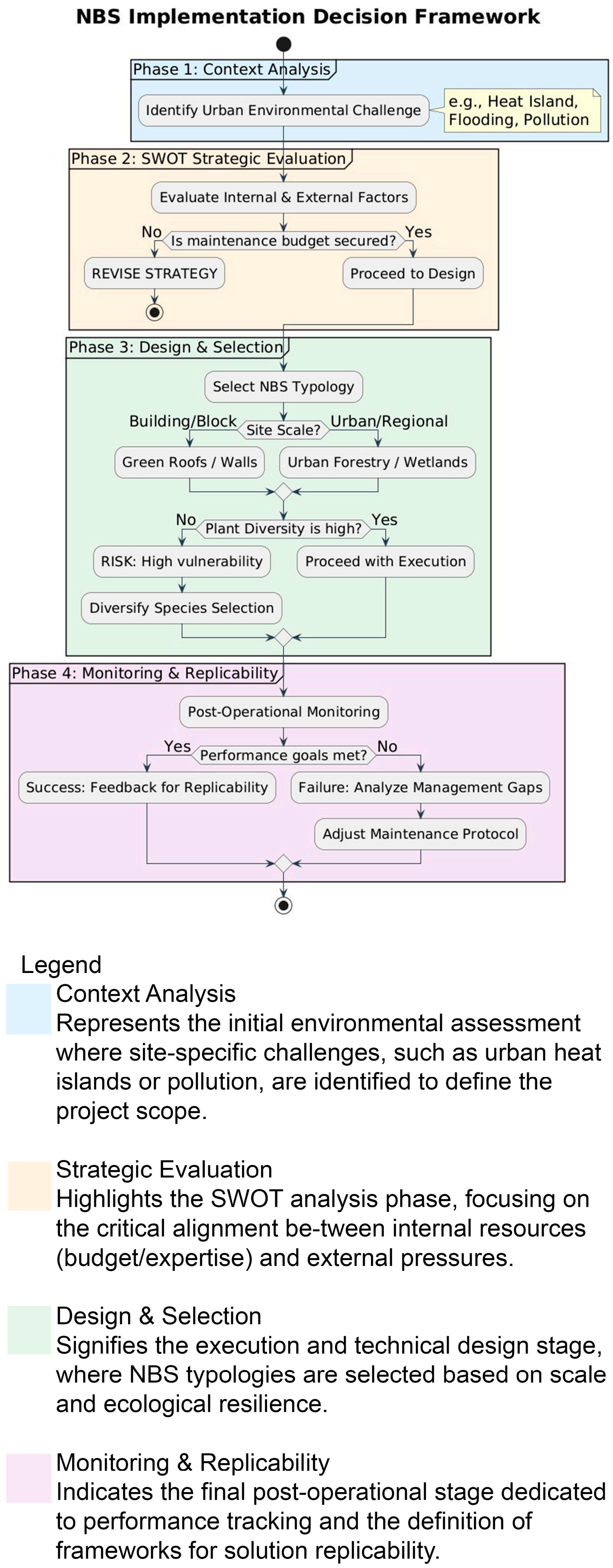
To enhance the utility of this interpretative framework for practitioners, Table 4 has been expanded to detail the specific sub-factors and operational examples that determine the success of scaling these interventions. The expansion of these factors emphasizes that replicability is not a "copy-paste" exercise but a calibrated adjustment to site-specific conditions. For instance, while the technical layers of a green roof are standardized, their success in a Mediterranean climate depends on the moisture content of the substrate and the inclusion of irrigation-efficient species. Similarly, the failure of rain gardens in commercial districts—often due to soil compaction and lack of dedicated maintenance budgets—highlights that without a clear governance protocol and allocated funding, even technically sound solutions become environmental liabilities. By standardizing these operational sub-factors within the decision-making workflow, planners can move from high-risk pilot schemes to resilient, structural urban assets.

Table 6. Key Factors for Successful Replicability.

Factor	Description	Strategic Goal
Contextual Adaptation	• Ecological Matching: Selecting autochthonous species resilient to local stressors (e.g., drought-resistant Sedum for Mediterranean roofs). • Morphological Integration: Mapping local micro-drainage patterns and "sky view factors" to ensure optimal cooling and infiltration.	Ensuring survival and performance.
Resource Optimization	• Lifecycle Costing (LCC): Balancing high initial CAPEX (e.g., green roof membranes) against long-term OPEX (e.g., urban forest pruning and irrigation). • Financial Incentives: Utilizing tax credits, green bonds, or carbon credits to offset maintenance costs.	Long-term economic sustainability.
Governance Models	• Multi-Stakeholder Engagement: Implementing co-management agreements with local communities or private owners to ensure "social demand" and legitimacy. • Integrated Policy: Embedding NBS requirements into municipal building codes and urban climate adaptation plans.	Durability and project legitimacy.

The economic sustainability of NBSs is fundamentally dictated by the governance and financial models established at the project's inception. Governance decisions regarding the structural integration of NBS into urban planning directly impact the balance between initial construction costs and long-term maintenance expenses. For example, urban forestry projects often involve low unit costs for initial planting but require a substantial and continuous financial commitment for pruning, irrigation, and specimen replacement over their lifecycle to ensure performance. Conversely, green roofs demand significantly higher upfront capital due to specialized technical layers and necessary structural assessments, although they typically offer more standardized and predictable management protocols over time. A failure to align governance frameworks with these economic realities often leads to a lack of sustainable funding, causing the degradation of NBS performance and the loss of intended ecosystem services. Consequently, an integrated framework is necessary to support decision-makers in selecting the most cost-effective solutions while ensuring that maintenance methods are adequately funded and managed throughout the solution's entire life cycle.

Furthermore, the adoption of a structured decision-making workflow is essential to bridge the gap between abstract scientific evidence and operational urban planning. By integrating technical, economic, and management factors within an interpretative framework, such a workflow provides planners with the necessary tools to navigate complex uncertainties and ensure the long-term sustainability of interventions. This systematic approach facilitates the replicability of solutions and the optimization of available resources, ultimately allowing for the structural integration of NBSs into broader urban regeneration and environmental planning processes (Figure 4).



🟦 Context Analysis
Represents the initial environmental assessment where site-specific challenges, such as urban heat islands or pollution, are identified to define the project scope.

🟧 Strategic Evaluation
Highlights the SWOT analysis phase, focusing on the critical alignment be-tween internal resources (budget/expertise) and external pressures.

🟩 Design & Selection
Signifies the execution and technical design stage, where NBS typologies are selected based on scale and ecological resilience.

🟪 Monitoring & Replicability
Indicates the final post-operational stage dedicated to performance tracking and the definition of frameworks for solution replicability.

Figure 4. Proposed Decision Flowchart.

5. Conclusions

The procedural implementation of NBS represents a critical shift in contemporary urban planning, directly addressing the multifaceted challenges posed by rapid urbanization, anthropogenic climate change, and widespread environmental pollution. This research has underscored that while ecosystems provide essential services—ranging from carbon sequestration and thermal regulation to hydraulic risk reduction—their functional integrity is increasingly compromised by land-use intensification and ecological fragmentation. Consequently, NBS have emerged not merely as environmental additives but as structurally integrated strategies capable of jointly addressing biodiversity loss and the growing vulnerability of cities to extreme climatic events. By restoring or imitating ecological processes, these multifunctional interventions aim to re-establish the relationship between natural and anthropogenic systems through adaptive and scalable measures.

The methodology adopted in this study focused on an integrated investigation of the technical, economic, and management dimensions that determine the effective implementation of NBS throughout their entire life cycle. Through a targeted review of scientific literature and the application of a SWOT analysis framework, the research categorized internal attributes, such as technical expertise and financial resources, and external factors, including policy shifts and economic risks. This approach allowed for a comprehensive assessment of the strategic landscape, moving beyond the documentation of generic environmental performance to understand the practical conditions for sustainability. The comparative analysis of urban forestry and green roof case studies, identified through a rigorous screening of academic databases, provided a nuanced view of how different NBS respond to varying application contexts.

Empirical results indicate a recurring procedural path for successful implementation, beginning with preliminary context analysis and moving through co-design phases involving local stakeholders. The study highlighted significant operational differences between the primary NBS typologies: urban forestry interventions provide broad territorial benefits in cooling and water regulation but require medium-to-long-term maturation and intensive maintenance. Conversely, green roofs offer localized and immediate runoff reduction and thermal inertia benefits, though they are characterized by higher initial installation costs and standardized technical requirements. These findings emphasize that the choice of solution must align with the specific spatial scale and temporal horizon of the intended urban benefits, ensuring that implementation strategies are both resilient and contextually appropriate.

The critical discussion further revealed a "standardization paradox," where the prevalent use of a limited number of resilient plant species simplifies design but increases systemic vulnerability to biotic and abiotic stressors. Furthermore, the long-term success of NBS is frequently undermined by fragmented governance models and a failure to adequately account for operational expenditures relative to initial capital costs. To ensure durability, interventions must be supported by integrated governance frameworks that bridge the gap between planning and post-operational monitoring, fostering the legitimacy and social demand for such services. This necessitates a shift toward adaptive management strategies capable of navigating technical and economic uncertainties throughout the project cycle.

In conclusion, NBSs must be applied with informed, site-specific awareness and meticulous design consideration. It is essential to avoid the implementation of generic, large-scale applications that prioritize short-term cost savings over long-term ecological and functional performance. While "one-size-fits-all" approaches may appear economically advantageous during the initial installation phase, they often provide diminishing ecosystem benefits and eventually become a significant financial burden as they fail to adapt to unique local environmental pressures. True sustainability in urban regeneration demands that each intervention be meticulously tailored to the specific climatic, morphological, and social conditions of the site. Only through such context-sensitive and conscious application can NBS truly fulfil their potential as resilient, cost-effective assets, avoiding the systemic degradation associated with poorly planned, large-scale implementations.

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