

Review

Nature-Based Solutions for Decentralized Wastewater Treatment: A Review of Technical, Economic, and Environmental Viability

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Abstract

Wastewater treatment remains a major challenge in rural and peri-urban areas, where conventional centralized infrastructure is often unavailable or insufficient. In this context, Nature-Based Solutions (NBS) have emerged as cost-effective and energy-efficient alternatives for decentralized wastewater treatment. This review presents a comprehensive and multidimensional assessment of 15 NBS types, evaluating their technical performance, economic viability, environmental sustainability, and social dimensions. The analysis indicates that NBS can achieve pollutant removal efficiencies comparable to those of conventional treatment systems, particularly for organic matter and, in some cases, emerging contaminants. However, their performance is strongly influenced by system design and operational conditions. The main limitations of NBS include relatively low hydraulic and pollutant loading capacities, as well as substantial land requirements, ranging from 0.45 to 840 m²·PE⁻¹. These constraints limit their applicability in densely populated areas while making them particularly well suited for rural and low-density settings. From both economic and environmental perspectives, NBS offer significant advantages, including construction cost reductions of up to 66% and substantially lower energy consumption than conventional technologies. Nevertheless, their successful implementation depends not only on technical performance but also on social acceptance, stakeholder engagement, and the establishment of appropriate governance frameworks. Overall, NBS constitute a flexible and sustainable approach to wastewater treatment, whose effectiveness ultimately depends on site-specific conditions and the integration of complementary treatment components.

Academic Editors: Kinjal J. Shah and Yongjun Sun

Received: 6 June 2026

Revised: 19 July 2026

Accepted: 20 July 2026

Published: 22 July 2026

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Keywords: nature-based solutions; decentralized wastewater treatment; environmental governance; water reuse; constructed wetlands; cost–benefit analysis; sustainable water management

1. Introduction

Wastewater management remains a critical global challenge, particularly in rural and peri-urban areas where centralized treatment infrastructure is often unavailable or inadequate. According to the United Nations World Water Development Report, approximately 80% of wastewater is discharged without treatment worldwide, with this figure

increasing to as much as 95% in low- and middle-income countries [1]. This widespread lack of treatment contributes substantially to water pollution and poses serious threats to both ecosystems and public health [2,3].

Conventional wastewater treatment technologies, including activated sludge systems, membrane bioreactors, and oxidation ditches, provide high treatment efficiencies but require complex infrastructure, substantial energy inputs, and skilled operation and maintenance [3–6]. These requirements limit their suitability for decentralized applications, particularly in regions with limited financial and technical resources. In this context, Nature-Based Solutions (NBS) have emerged as promising alternatives owing to their low energy demand, reduced operational complexity, and capacity to provide multiple environmental and social co-benefits [4,7,8].

NBS for wastewater treatment are engineered systems inspired by natural processes that combine physical, chemical, and biological mechanisms to remove pollutants [7]. Representative examples include constructed wetlands, waste stabilization ponds, land treatment systems, and more recent approaches such as microalgae-based systems and nature-integrated urban treatment technologies [4,9,10].

Constructed wetlands are among the most extensively studied and widely implemented NBS for wastewater treatment. They encompass a broad range of configurations that differ in flow regime, vegetation type, and hydraulic design. These systems can be classified according to their hydrological regime (surface or subsurface flow), flow direction (horizontal or vertical), and the type of macrophytes used (emergent, floating, or submerged). A schematic overview of the principal constructed wetland configurations is presented in Figure S1 (Supplementary Material), illustrating the relationships among these design characteristics. The classification follows the framework proposed by Vymazal [11], distinguishing systems according to flow direction, macrophyte type (emergent, free-floating, floating-leaved, or submerged), and hydrological regime (surface or subsurface flow). Beyond wastewater treatment, constructed wetlands provide valuable ecosystem services, including habitat creation, carbon sequestration, and landscape enhancement [4].

Despite these advantages, NBS also presents important limitations that should be carefully considered [9]. Their treatment performance is strongly influenced by climatic conditions, hydraulic loading rates, and system design, while their relatively high land requirements often restrict their implementation in densely populated areas [4,9]. Additional operational challenges include mosquito proliferation, seasonal vegetation die-off, sludge accumulation, and substrate clogging [4]. Furthermore, the removal efficiency of certain pollutants, particularly nutrients and emerging contaminants, remains highly dependent on system configuration and operational conditions [9–13]. These limitations underscore the need for a comprehensive and critical assessment of the applicability of NBS under different environmental and operational contexts.

Several review studies have examined specific aspects of NBS, including pollutant removal performance, individual treatment technologies, and environmental impacts [4,5,14]. However, most existing reviews focus on a single dimension or a limited set of technologies, and comprehensive comparative analyses that simultaneously evaluate technical, economic, environmental, and social aspects remain scarce [9,15,16]. Moreover, relatively little attention has been paid to the role of decentralized implementation and to the conditions under which NBS can effectively compete with conventional wastewater treatment technologies, as previous studies have generally focused on specific systems, geographical regions, or isolated performance indicators rather than on their overall applicability [9,17].

To address these gaps, the present review adopts a multidimensional perspective to evaluate a broad range of NBS for wastewater treatment. The analysis systematically com-

compares different NBS based on key design and operational parameters, including loading rates, land requirements, energy consumption, and pollutant removal performance, while also assessing their economic feasibility, environmental sustainability, and social acceptability. Particular emphasis is placed on decentralized wastewater treatment in rural and peri-urban areas, although two building-scale urban applications—rooftop wetlands and living walls—are also included to provide a more comprehensive overview of the available technologies.

Finally, this review highlights the importance of site-specific conditions, technological trade-offs, and system integration in determining the suitability of NBS. By combining quantitative performance data with a critical evaluation of implementation challenges and practical design considerations, the study provides both a comprehensive synthesis of the current state of knowledge and actionable insights to support decision-making and the design of decentralized wastewater treatment systems, thereby complementing and extending the perspectives offered by previous review studies.

Figure 1 illustrates the conceptual framework adopted in this review, highlighting the relationships among technical performance, environmental impacts, economic feasibility, and social acceptance.

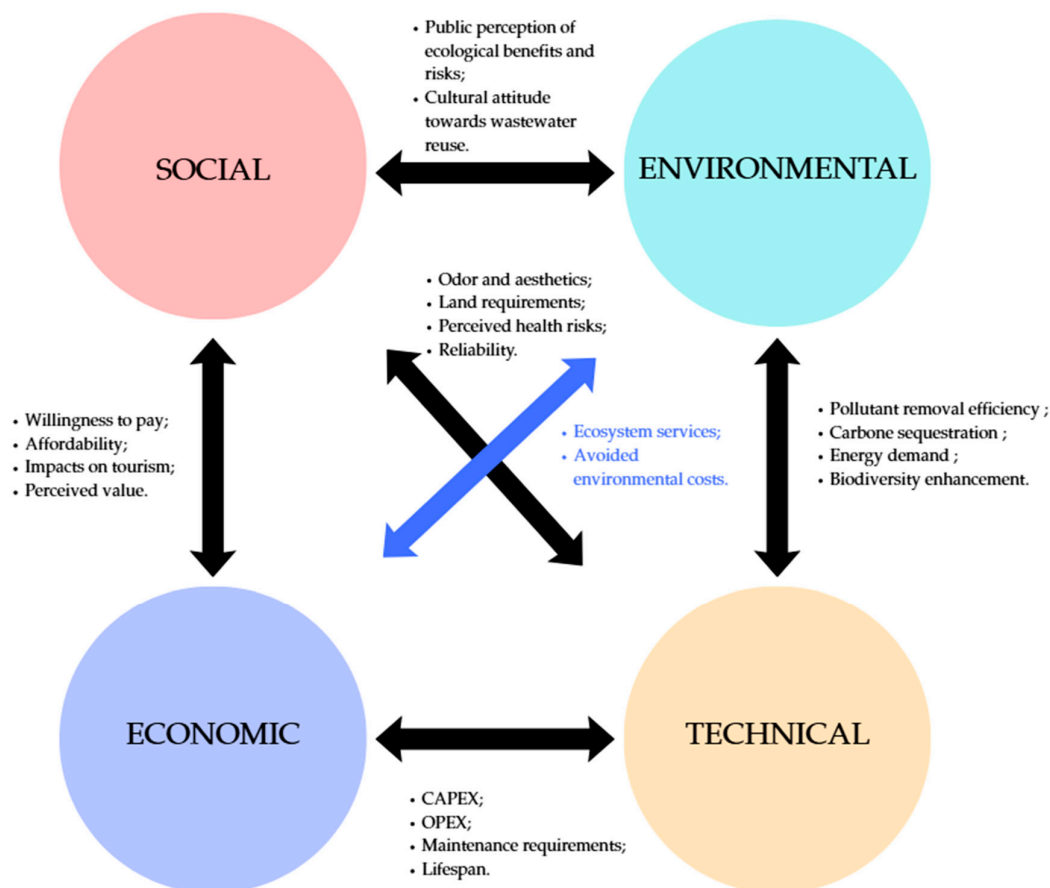


Figure 1. Conceptual framework illustrating the relationships among technical performance, environmental impacts, economic feasibility, and social acceptance.

This study pursues three main objectives: (i) to compare the performance of different NBS across multiple evaluation criteria; (ii) to identify the key factors influencing their efficiency and applicability; and (iii) to provide practical guidance for the selection and implementation of NBS in decentralized wastewater treatment.

2. Materials and Methods

This study adopts a structured narrative review approach to evaluate the performance of NBS for decentralized wastewater treatment. Rather than providing a fully systematic review, it aims to synthesize and critically assess the existing body of knowledge across multiple dimensions, including technical performance, economic feasibility, environmental sustainability, and social aspects.

2.1. Literature Search Strategy

Relevant literature was identified through searches of the Web of Science and Scopus databases. The literature search was conducted using the following search strategy:

("nature-based solutions" OR "constructed wetlands" OR "stabilization ponds" OR "land treatment" OR "microalgae systems" OR "decentralized wastewater treatment" OR "conventional wastewater treatment systems" OR "living walls" OR "rooftop wetlands")
AND

("energy requirements" OR "pollutant removal" OR "land requirements" OR "life cycle assessment" OR "cost" OR "economic evaluation" OR "operation and maintenance costs" OR "capital costs" OR "heavy metal removal" OR "emerging contaminants" OR "social acceptance" OR "environmental governance" OR "environmental impacts")

To ensure comprehensive coverage of the available evidence, additional relevant publications were identified through backward citation tracking of the references cited in the retrieved studies.

The literature search was last updated on 15 July 2026. Records retrieved from Web of Science and Scopus were merged into a single database, and duplicate records were identified based on DOI, title, authors, and publication year before screening. Publications written in English, Spanish, or French were considered. Eligible document types included peer-reviewed research articles, review articles, project reports, and authoritative technical documents. Conference abstracts, editorials, book reviews, and publications without sufficient methodological or quantitative information were excluded. Given that most of the scientific resources are published in English, research in English has been prioritized.

2.2. Selection Criteria

The selection of studies was guided by their relevance to the objectives of this review. The literature was evaluated according to the following criteria:

- Decentralized applications: Priority was given to studies investigating decentralized wastewater treatment systems, particularly those implemented in rural and peri-urban settings.
- Evidence selection: Publications published between 2000 and 2026 were considered to capture both well-established technologies and recent developments. When several studies reported similar information for the same evaluation parameter or NBS, priority was given to studies providing the most complete methodological description, comprehensive reporting of operating conditions, and the greatest relevance to the objectives of this review. More recent publications were preferred only when they provided additional or updated information compared with earlier studies. Older studies were retained when they represented the principal or only available source of information for a particular NBS.
- Study scale: Whenever possible, full-scale studies and review articles were prioritized over laboratory- and pilot-scale studies because they generally provide performance data obtained under real operating conditions and are therefore more informative for evaluating the practical applicability of NBS in decentralized wastewater treatment.

These criteria were applied as guiding principles rather than strict inclusion or exclusion rules. For some NBS, however, recent studies or investigations specifically addressing decentralized applications were unavailable, requiring the inclusion of older publications or studies conducted under different operational contexts.

Because this study was designed as a structured narrative review rather than a systematic review or meta-analysis, no formal risk-of-bias tool was applied. Nevertheless, the relevance and reliability of each source were assessed qualitatively by considering: (i) clarity of the study design and system configuration; (ii) availability of information on wastewater characteristics and operating conditions; (iii) study scale; (iv) transparency of the analytical methods; (v) completeness of the reported data; and (vi) relevance to decentralized wastewater treatment. Full-scale studies, comprehensive reviews, and authoritative technical reports were generally considered stronger sources for practical performance assessment, whereas laboratory and pilot studies were retained when full-scale evidence was unavailable or when they addressed emerging NBS.

Initial screening and data extraction were performed by one author. Uncertain eligibility decisions and potentially conflicting information were discussed with and verified by the second author. Disagreements were resolved by consensus.

2.3. Data Extraction and Synthesis

Data from the selected studies were extracted using a qualitative and semi-quantitative approach and organized into four main categories: technical performance (treatment efficiency, loading rates, land requirements, and energy consumption), economic aspects (capital and operational costs), environmental impacts (energy consumption, ecosystem services, and life cycle considerations), and social dimensions (community engagement, governance, and implementation factors).

For each selected study, the information extracted included, where available, the type of NBS, wastewater characteristics, study scale (laboratory, pilot, or full scale), pollutant removal performance, loading rates, land requirements, energy consumption, economic indicators, environmental impacts, and social or governance aspects. When multiple studies reported different values for the same parameter, the reported performance range was retained to reflect the variability of the available evidence.

Given the heterogeneity of the available evidence, a formal quantitative meta-analysis was not feasible. Instead, representative performance ranges and reported values were compiled to facilitate comparison among the different NBS. Consequently, the values presented in the tables should be interpreted as indicative ranges rather than statistically pooled estimates. The analysis therefore emphasizes the identification of general trends, performance ranges, and the key factors influencing the applicability of each NBS, rather than the derivation of statistically aggregated metrics. This approach is consistent with the narrative review methodology adopted in this study.

Because this study was designed as a structured narrative review rather than a systematic review or meta-analysis, no formal risk-of-bias assessment was performed. Instead, the reliability of the evidence was qualitatively assessed by considering the study design, study scale, methodological transparency, completeness of the reported data, and relevance to decentralized wastewater treatment.

Figure 2 presents the PRISMA flow diagram summarizing the literature selection process.

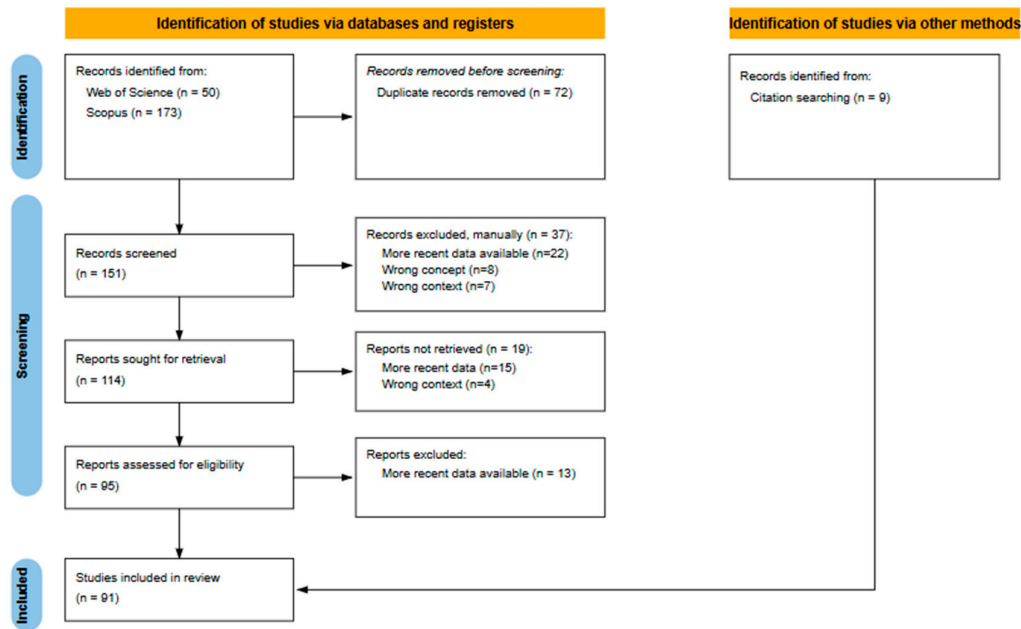


Figure 2. PRISMA flow diagram of the literature selection process.

2.4. Limitations of Data Sources

The results are presented as representative performance ranges derived from a comprehensive synthesis of the available literature. These ranges are based on reported observations rather than theoretical assumptions and are intended to capture the inherent variability of NBS while providing realistic estimates of their performance.

The data were compiled from a wide range of sources, including project reports, review articles, and technical documents, which employed different methodologies and evaluation criteria. Despite this methodological heterogeneity, the comparison remains meaningful because the objective of this review is to compare orders of magnitude and identify general performance trends rather than to establish universal reference values, which are currently unavailable. Whenever possible, performance ranges were derived by integrating data from multiple studies to improve the representativeness and robustness of the reported estimates.

Operation and maintenance costs were not included in the economic assessment. Although this topic has been addressed in a limited number of studies, including one project-scale study [18] and one experimental study [19], comparative data remain insufficient to support a robust evaluation of operation and maintenance costs across different NBS for wastewater treatment.

The performance of NBS is influenced by numerous site-specific factors, including climatic conditions, soil characteristics, wastewater composition, hydraulic loading, and social and cultural conditions that may affect public acceptance. These factors contribute to the variability of the reported results and represent an inherent limitation of the available evidence. To reduce their influence, priority was given to comprehensive studies that explicitly considered these contextual factors in their methodology and analysis.

2.5. A Multidimensional Assessment of Nature-Based Solutions for Decentralized Wastewater Treatment

NBS for wastewater treatment comprises a diverse range of technologies that rely on different physical, biological, and chemical processes. Rather than describing each technology individually, Sections 3–6 present a comparative assessment based on four key evaluation dimensions: technical performance, economic feasibility, environmental sustainability, and social aspects.

The NBS considered in this review include constructed wetlands [11], land treatment systems [20,21], waste stabilization ponds, microalgae-based treatment systems, and emerging urban applications such as rooftop wetlands and living walls. These technologies are evaluated in the following sections according to their performance characteristics and their suitability for decentralized wastewater treatment.

2.6. Methodology for the Decision Tree

The decision tree presented in Section Decision Tree is intended to support the selection of the most appropriate Nature-Based Solution NBS based on a set of technical criteria. Five criteria were considered to guide the selection process:

- Territorial context: urban, peri-urban, or rural.
- Type of wastewater: raw wastewater, greywater, primary-treated wastewater, or secondary-treated wastewater.
- Loading rate: $>0.1 \text{ m}\cdot\text{year}^{-1}$, $>0.01 \text{ m}\cdot\text{year}^{-1}$, and $>0.001 \text{ m}\cdot\text{year}^{-1}$. These thresholds were selected to provide a balanced distribution across the three categories. When the reported loading-rate range of a given technology spanned two categories, it was assigned to the higher category.
- Land requirement: $>30 \text{ m}^2\cdot\text{PE}^{-1}$ or $<10 \text{ m}^2\cdot\text{PE}^{-1}$. These thresholds were chosen to distinguish willow systems and slow-rate soil infiltration systems, which require substantially larger land areas than the other NBS. When the reported land requirement of a technology spanned two categories, it was assigned to the higher category.
- Energy requirement: $>0 \text{ kWh}\cdot\text{m}^{-3}$, $>0.04 \text{ kWh}\cdot\text{m}^{-3}$, and $>0.16 \text{ kWh}\cdot\text{m}^{-3}$. These thresholds were selected to provide a balanced distribution across the three categories. When the reported energy requirement of a technology spanned two categories, it was assigned to the higher category.

3. Technical Evaluation of Nature-Based Solutions for Decentralized Wastewater Treatment

The technical performance of NBS varies considerably depending on system design, operating conditions, and wastewater characteristics. Unlike conventional treatment technologies, whose performance is generally well standardized, NBS exhibit greater variability because they rely on natural processes such as microbial activity, plant uptake, and physicochemical interactions.

To enable a consistent comparison across technologies, this section evaluates NBS using five key technical and operational criteria. These were selected because they represent the principal factors commonly considered in the design, performance assessment, and implementation of decentralized wastewater treatment systems.

(i) Type of wastewater treated: Wastewater composition can vary substantially among communities, buildings, and facilities. In contrast to centralized treatment plants, which typically receive large and relatively homogeneous influent flows, decentralized systems are often designed to treat wastewater generated by specific users or small populations. Consequently, wastewater type strongly influences technology selection and expected treatment performance.

(ii) Pollutant removal efficiency: Pollutant removal efficiency is the primary indicator used to evaluate treatment performance. The different NBS exhibit varying levels of technological maturity and consequently different treatment capabilities. This criterion directly reflects the ability of a system to achieve environmental protection and public health objectives.

(iii) Loading rate: Hydraulic and pollutant loading rates are key design parameters because wastewater generation may fluctuate substantially owing to seasonal population changes, tourism, or variations in water consumption. Excessive loading can reduce treatment efficiency, overload the system, and ultimately compromise long-term performance.

(iv) Land requirement: Land availability is a critical consideration for NBS because many treatment processes require substantially larger footprints than conventional engineered technologies. In decentralized applications, available land is often one of the main factors determining the feasibility of a particular treatment option.

(v) Energy consumption: Energy demand is a key indicator of resource efficiency and operational sustainability. Minimizing energy consumption is particularly important in decentralized applications, where access to reliable electricity may be limited. Low-energy technologies also reduce operating costs and greenhouse gas emissions.

These criteria are particularly relevant for evaluating the applicability of NBS in decentralized contexts, where land availability, operational simplicity, and system robustness are essential considerations.

The performance ranges reported throughout this section represent indicative values compiled from the literature rather than statistically pooled estimates. The variability among studies reflects the strong influence of site-specific factors, including wastewater characteristics, climatic conditions, soil properties, vegetation type, hydraulic and organic loading rates, system design, and operational practices. Consequently, the reported ranges should be interpreted as representative values for comparative purposes rather than as fixed performance thresholds.

Table 1 summarizes the main advantages and limitations of the 15 NBS included in this review. Table 2 presents the technological maturity of the four main groups of NBS (constructed wetlands, land treatment systems, stabilization ponds, and microalgae systems). The maturity assessment is presented at the group level because technologies within each category generally exhibit comparable levels of technological development and implementation.

Table 1. Main advantages and limitations of the 15 NBS included in this review.

NBS	Main Advantages	Main Limitations
Constructed Wetlands	• Wide range of applicability; • Efficient in the removal of COD, BOD, NH₄-N, TSS; • High loading rate; • Low area requirements; • Low energy requirements; • Low costs of construction.	• Limited in the removal of TP and TN
	• Wide range of applicability; • Efficient in the removal of COD, BOD, TSS and microorganisms; • High loading rate; • Low area requirements; • Low energy requirements; • Low costs of construction.	• Limited in the removal of TP, TN and NH₄-N
	• Wide range of applicability	• No data available on the removal of TSS.

Land treatment		• Efficient in the removal of COD, NH₄-N and microorganisms; • High loading rate; • Low area requirements; • Low energy requirements; • Low costs of construction.	
	Floating	• Wide range of applicability; • Low area requirements; • Low energy requirements; • Low costs of construction.	• No data available on the removal of BOD, microorganisms, and TSS.
	Willow systems	• Wide range of applicability; • Efficient in the removal of TP, TSS, COD, BOD, TN and NH₄-N; • Low energy requirements; • Low costs of construction.	• Low loading rate; • High area requirements.
	Slow-rate soil infiltration	• Wide range of applicability; • Efficient in the removal of TP, TSS, COD, BOD, TN, NH₄-N and microorganisms; • Low energy requirements; • Low costs of construction.	• Low loading rate; • High area requirements
	Rapid-rate soil infiltration	• Wide range of applicability; • Efficient in the removal of TSS, microorganisms, COD, BOD and NH₄-N; • High loading rate; • Low area requirements; • Low energy requirements; • Low costs of construction	• Wide ranges for the removal of TN, and TP.
	Overland flow	• Efficient in the removal of TN and microorganisms; • Low energy requirements; • Low costs of construction.	• Only treat primary treated water; • Low loading rate.
	Surface aerated flow	• Wide range of applicability; • Efficient in the elimination of BOD and microorganisms; • Low area requirements; • Low energy requirements; • Low costs of construction.	• Limited in the removal of TN and TP.
	Anaerobic	• Wide range of applicability; • Efficient in the elimination of microorganisms; • Low area requirements; • Low energy requirements; • Low costs of construction.	• Limited in the removal of TN and TP.
	Facultative	• Wide range of applicability; • Efficient in the elimination of microorganisms; • Low area requirements; • Low energy requirements; • Low costs of construction.	• Limited in the elimination of COD, TN, TP, and TSS.
	Maturation	• Efficient in the removal of microorganisms; • Low area requirements; • Low energy requirements; • Low costs of construction.	• Only treat secondary treated water; • Limited in the removal of COD, BOD, TN, and TS.

Microalgae	• Efficient in the removal of microorganisms and COD; • Low area requirements; • Low energy requirements.	• No data available on the removal of BOD, NH₄-N, and TSS.
Rooftop wetlands	• Wide range of applicability • Efficient in the removal of COD, TN, NH₄-N, TP, and TSS.	• Not applicable in rural contexts.
Living walls	• Efficient in the removal of TSS, BOD, and TN.	• Only treat grey water and secondary treated water; • Not applicable in rural contexts.

Table 2. Technological maturity of the four main categories of nature-based solutions (NBS) for decentralized wastewater treatment.

Treatment System	Level of Maturity
Constructed wetlands	Constructed wetlands (CWs) have been widely implemented for several decades and are supported by extensive experimental research, pilot-scale investigations, and full-scale applications. According to Moreira et al. [22], CWs are the most mature nature-based wastewater treatment technology for rural areas after septic tanks. Furthermore, Praveen et al. [23] assigned constructed wetlands a Technology Readiness Level (TRL) of 8, indicating technology demonstrated under operational conditions.
Land treatment	A Technology Readiness Level (TRL) has not yet been explicitly reported for land treatment systems. Nevertheless, these technologies have been successfully implemented at full scale for several decades and are supported by well-established engineering design standards and operational guidelines [24], indicating a high level of technological maturity.
Stabilization ponds	Stabilization ponds have been widely used worldwide for several decades and represent one of the most established nature-based wastewater treatment technologies. Their extensive operational experience and well-established design methodologies demonstrate a high level of technological maturity. Ongoing research focuses primarily on improving treatment performance, reducing land requirements, and optimizing operation under different climatic conditions [25].
Microalgae systems	The feasibility and treatment performance of microalgae-based systems have been demonstrated primarily at laboratory and pilot scales, whereas large-scale operational implementation remains limited. According to Praveen et al. [23] and Valchev et al. [26], microalgae-based wastewater treatment systems have a TRL of 6, indicating technology demonstrated in relevant environments but requiring further validation for widespread implementation.

3.1. Type of Wastewater Treated

The type of wastewater to be treated is a key factor in determining the suitability of NBS. Wastewater characteristics, including the origin and composition of domestic, industrial, or mixed effluents, influence system design, operational requirements, and treatment performance. Matching the characteristics of the wastewater to the capabilities of each NBS is therefore essential to ensure effective treatment and long-term system sustainability.

The following section examines the suitability of different NBS for treating various wastewater types, providing guidance for technology selection according to influent characteristics and treatment objectives. To facilitate comparison, Table 3 summarizes the ap-

plicability of the different NBS to each wastewater category. Blue cells indicate the wastewater types that can be effectively treated by each technology based on representative evidence from the literature.

Table 3. Applicability of NBS to different wastewater types.

NBS	Raw	Grey	Primary Treated	Secondary Treated	References
Constructed Wetlands	Vertical flow	X	X	X	Laboratory-scale study [27]; Global studies [4,9,28];
	Horizontal flow	X	X	X	Global studies [4,9]
	Free water surface	X	X	X	Global studies [4,9,28]; EPA global study [29]
	Floating	X	X	X	Global studies [4,28]; EPA global study [29]
	Willow systems	X	X	X	Global studies [4,9,28]; Experimental study [30]
Land treatment	Slow-rate soil infiltration	X	X	X	Global study [4,28]; Simulation study [31]; Project study [32]
	Rapid-rate soil infiltration	X	X	X	Global study [4,25]; Project study [32]; Modelling study [33]
	Overland flow		X		Global studies [4,28]
Stabilization ponds	Surface aerated flow	X	X	X	Global study [4]; experimental study [34]
	Anaerobic	X	X	X	Global study [4]; experimental study [34]
	Facultative	X	X	X	Global study [4]; experimental study [34]
	Maturation			X	Global study [4]
Microalgae		X	X	X	Global studies [4,28,35,36]
Rooftop wetlands		X	X	X	Global study [4,37]
Living walls		X		X	Global study [4,37]

The range of wastewater that can be effectively treated by NBS depends on several factors, including influent characteristics, system design, and resistance to clogging and operational variability. In many cases, preliminary treatment (e.g., primary or secondary treatment) is required to ensure stable operation and prevent hydraulic failure.

As shown in Table 3, constructed wetlands are generally not designed to receive raw wastewater and typically require at least primary treatment to minimize the risk of clogging and maintain hydraulic performance [9,28]. Although some specific configurations, such as multistage vertical-flow constructed wetlands, have been reported to treat raw influent, these represent exceptions rather than standard practice [4].

Similarly, land treatment systems are generally designed to receive pre-treated wastewater. Rapid infiltration basins and infiltration-percolation systems are commonly applied as post-treatment technologies for primary- or secondary-treated effluents, providing additional purification while promoting groundwater recharge [32,33]. Likewise, overland flow systems are typically used as secondary treatment processes to further reduce organic matter and suspended solids [4,28].

Several NBS, including vertical-flow constructed wetlands, overland flow systems, and anaerobic and facultative waste stabilization ponds, are primarily intended for sec-

ondary treatment, with the main objective of removing organic matter and nutrients [4,9,28]. Depending on system configuration and operating conditions, however, some of these technologies can also contribute to tertiary treatment, particularly when incorporated into hybrid or multistage treatment schemes [38–40].

Maturation ponds are specifically designed to enhance pathogen removal and are therefore commonly employed as a polishing step following secondary treatment [4]. In contrast, building-scale NBS such as rooftop wetlands and living walls are primarily used for greywater treatment, where influent loads are lower and wastewater characteristics are generally more homogeneous [37].

A key finding from Table 3 is that relatively few technologies exhibit broad applicability across different wastewater types. Microalgae-based systems and surface-aerated waste stabilization ponds are among the most versatile, as they can operate under a wide range of influent conditions [4,28,35]. In microalgae-based systems, this versatility is associated with the diversity of algal species and metabolic pathways, which enable the simultaneous removal of nutrients, organic matter, and, in some cases, emerging contaminants [35]. In surface-aerated ponds, enhanced oxygen transfer improves both treatment efficiency and process stability [4].

Overall, the analysis indicates that most NBS are not universally applicable and frequently require pre-treatment to ensure reliable long-term operation. Technologies such as land treatment systems and building-integrated NBS are generally limited to pre-treated or low-strength wastewater [32,33,37], whereas more robust systems, including waste stabilization ponds and certain constructed wetland configurations, are capable of treating a broader range of wastewater characteristics.

These findings highlight the importance of selecting NBS according to influent characteristics and treatment objectives. They also underscore the value of hybrid configurations, in which different treatment technologies are combined to exploit their complementary strengths. In this regard, the review by [28], which evaluated more than 50 pilot- and full-scale treatment systems, concluded that hybrid configurations generally achieve higher treatment efficiencies and greater operational reliability than single-stage systems.

The variability observed among NBS further demonstrates the strong influence of site-specific conditions on treatment performance, emphasizing the need for context-specific system design and caution when extrapolating performance data across different environmental and operational settings.

3.2. Pollutants Removal

Pollutant removal efficiency is one of the principal indicators used to evaluate the technical performance of NBS. These systems remove contaminants through a combination of physical, chemical, and biological processes, including sedimentation, filtration, microbial degradation, plant uptake, and natural oxidation [9].

Treatment performance, however, varies considerably among NBS owing to differences in system design, operating conditions, and environmental factors [9]. Consequently, reported removal efficiencies often cover broad ranges, making direct comparisons difficult. For this reason, the analysis presented in this section emphasizes not only the reported performance values but also the identification of general trends, key limitations, and the main factors governing pollutant removal.

Tables 4 and 5 summarize the pollutant removal performance of the different NBS. The evaluated indicators include chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), ammonium nitrogen ($\text{NH}_4^+\text{-N}$), total phosphorus (TP), total suspended solids (TSS), and fecal coliforms.

The reported removal efficiencies are influenced by numerous contextual factors that are not explicitly reflected in the summarized data, including wastewater characteristics,

temperature, hydraulic retention time, system configuration, vegetation type, microalgal species, filter media, and whether the results were obtained from experimental, pilot-scale, or full-scale systems. This variability is particularly pronounced in land treatment systems, where treatment performance strongly depends on soil properties, hydraulic loading, hydraulic retention time, and hydrogeological conditions [32,33]. Consequently, some performance ranges are relatively broad. Nevertheless, these data provide a robust basis for comparing the overall performance of different NBS, identifying common trends, and highlighting the main technical factors influencing treatment efficiency.

Table 4. Removal efficiencies of organic matter and nitrogen by different NBS.

NBS	COD (%)	BOD (%)	TN (%)	NH ₄ -N (%)	Ref.	
Constructed wetlands	Vertical flow	70–90	83	20–40	80–90	Global studies [4,9]
	Horizontal flow	60–80	65	30–50	20–40	Global studies [4,9]
	Free water surface	41–90	54	30–80	73	Global studies [4,9]
	Floating	25–70	-	0.5–80	18–81	Global study [9], Experimental study [40]
	Willow systems	92–100	98–100	85–100	90–100	Global studies [4,9]
Land treatment	Slow-rate soil infiltration	94–99	90–99	50–99	80	Global study [4] Project study [32]
	Rapid-rate soil infiltration	78	95–99	25–90	77	Global study [4] Project study [32]
	Overland flow	-	46–98	63–91	-	Global study [10,41]
Stabilization ponds	Surface aerated flow	50–85	77	20–90	50–95	Global study [4]
	Anaerobic	50	50–70	10–23	-	Global study [4]
	Facultative	34	40–56	20–39	44	Global study [4]
	Maturation	16	33	15–50	20–80	Global study [4]
Microalgae	70–95	-	30–95	-	Global study [10,28]; Experimental study [42]	
Rooftop wetlands	80–99	-	65–91	83–96	Experimental study [43]	
Living walls	-	95–99	0–95	-	Experimental study [44]	

Table 5. Removal efficiencies of phosphorus, suspended solids, and pathogens by different NBS.

NBS	TP (%)	TSS (%)	Microorganisms' Removal (Log)	Ref.	
Constructed wetlands	Vertical flow	10–35	80–90	≤2–4	Global studies [4,9] Experimental study [45]
	Horizontal flow	10–50	>75	1.1	Global studies [4,9,46]; Experimental study [45]
	Free water surface	27–60	-	0.7–2.7	Global studies [4,9,41]
	Floating	24–78	-	-	Global study [9], Experimental study [40]
	Willow systems	≈100	100	-	Global studies [4,9]
Land treatment	Slow-rate soil infiltration	80–99	90–99	4	Global study [4]
	Rapid-rate soil infiltration	0–99	95–99	3–4	Global studies [4,47]

	Overland flow	40–50	-	1	EPA Global study [29]
	Surface aerated flow	30–45	53–90	≤1–2	Global study [4]
Stabilization ponds	Anaerobic	10–23	44–70	≤1–1.5	Global study [4]
	Facultative	1–25	27	≤1–2	Global study [4]
	Maturation	20–50	16	≤1–3	Global study [4]
					Global study [28]; EPA Global study [29]; Experimental study [42]
	Microalgae	40–100	-	>4	
	Rooftop wetlands	94–99	79–97	-	Experimental study [43]
	Living walls	0–92	81–99	-	Experimental study [44]

The reported removal efficiencies reveal distinct performance patterns among the different NBS. Vertical-flow constructed wetlands exhibit high removal efficiencies for organic matter and total suspended solids, with reported values ranging from 70 to 90% for COD and 80 to 90% for TSS. In contrast, nutrient removal is generally more limited, with total nitrogen (TN) and total phosphorus (TP) removal typically ranging from 20 to 40% and 10 to 35%, respectively. This limitation is primarily attributed to the absence of anaerobic zones, which are required for denitrification and effective phosphorus removal. Conversely, the high ammonium-nitrogen ($\text{NH}_4\text{-N}$) removal efficiency, typically between 80% and 90%, demonstrates the effectiveness of nitrification in this type of system [4].

In anaerobic waste stabilization ponds, ammonium removal data are rarely reported in the literature. This is largely explained by the absence of dissolved oxygen, which prevents nitrification. Under these conditions, ammonium removal is mainly limited to volatilization, a considerably less efficient process that substantially restricts the nitrogen removal capacity of these systems [48].

Free water surface constructed wetlands provide another illustrative example. Although their limited oxygen availability would suggest relatively low organic matter removal, several studies have reported COD removal efficiencies of up to 90% [4]. This high performance has been attributed to the combined effects of anaerobic biodegradation and sedimentation processes occurring within the wetland [9,24].

To facilitate comparison among technologies, the removal efficiencies of COD, TN, TP, and TSS were synthesized in Figure S2 (Supplementary Material), which provides a visual comparison of the performance of the 15 NBS configurations summarized in Tables 2 and 3.

Three technologies exhibit consistently high removal efficiencies for all four pollutants: willow systems, slow-rate soil infiltration systems, and rooftop wetlands. Reported removal efficiencies range from 92 to 100%, 94 to 99%, and 80 to 99% for COD; 85 to 100%, 50 to 99%, and 65 to 91% for TN; 100%, 80 to 99%, and 94 to 99% for TP; and 100%, 90 to 99%, and 79 to 97% for TSS, respectively [4,43]. In microalgae-based systems, high pollutant removal is mainly driven by nutrient uptake, photosynthetic activity, and interactions between microalgae and associated microbial communities, which contribute to their high treatment capacity and operational adaptability [9].

By contrast, vertical-flow and horizontal-flow constructed wetlands achieve high removal efficiencies for COD and TSS but are generally less effective at removing TN and TP [4]. Facultative and maturation ponds also exhibit comparatively low removal efficiencies for the four pollutants considered in Figure S2, generally below 50%. In the case of maturation ponds, however, these values should be interpreted in the context of their primary function, which is pathogen removal rather than the removal of organic matter or nutrients. Consequently, maturation ponds are typically used as the final polishing stage within multistage treatment systems rather than as standalone treatment units [4].

Some technologies exhibit relatively narrow performance ranges, indicating consistent treatment efficiencies across different studies. This is the case for willow systems, vertical-flow constructed wetlands, and anaerobic waste stabilization ponds [4]. In contrast, other NBS display substantial variability in pollutant removal performance, particularly floating constructed wetlands [40], living walls [43], and rapid-rate soil infiltration systems [4,47].

Rapid-rate soil infiltration systems provide a clear example of this variability. Reported phosphorus removal efficiencies range from 0% to 99%, indicating that some systems achieve little or no phosphorus removal, whereas others are highly effective. A similar pattern is observed for total nitrogen, with reported removal efficiencies ranging from 25% to 90%. These wide performance ranges highlight the strong influence of site-specific factors, including climatic conditions, soil characteristics, and system design [9].

Overall, the comparative analysis demonstrates the considerable potential of NBS for pollutant removal. Several technologies achieve consistently high treatment efficiencies and are therefore well suited for use as standalone treatment systems, whereas others perform more effectively when integrated into hybrid treatment trains. At the same time, the substantial variability observed for some technologies highlights the importance of site-specific design and indicates that the reported performance ranges should be interpreted as indicative values rather than precise design criteria.

Efficiency of total nitrogen and total phosphorus removal in Rapid-Rate Soil Infiltration Systems

As highlighted in the previous section, rapid-rate soil infiltration systems exhibit a particularly wide range of reported removal efficiencies for total nitrogen (TN) and total phosphorus (TP). This variability contrasts with the more consistent performance reported for many other NBS and indicates a strong dependence on site-specific conditions and system design. Factors such as soil characteristics, hydraulic loading rate, infiltration depth, redox conditions, and operational practices play a fundamental role in governing nitrogen and phosphorus transformation, retention, and removal processes.

This subsection examines the mechanisms controlling TN and TP removal in rapid-rate soil infiltration systems and discusses the factors responsible for the large variability reported in the literature. By synthesizing the available evidence, the analysis identifies the key parameters influencing nutrient removal efficiency and clarifies the conditions under which these systems can provide effective and reliable decentralized wastewater treatment.

Table 6 compiles the TN and TP removal efficiencies reported in scientific literature to illustrate the extent of this variability. The dataset includes information from 12 different sources, comprising full-scale projects, a comprehensive report published by the U.S. Environmental Protection Agency (EPA), and an experimental study.

Table 6. Reported total nitrogen (TN) and total phosphorus (TP) removal efficiencies in rapid-rate soil infiltration systems.

Project Number	TP Elimination	TN Elimination	Project/Global Study/Experimental Study	Reference
1	98%	77.7%	Project study	[49]
2	46–93%	37–74%	Experimental study	[50]
3	0–90%	25–90%	Global study	[47]
4	40–97%	10–20%	Project study	[51]
5	-	43%	Project study	[51]
6	89–97%	71%	Project study	[51]
7	99%	12%	Project study	[51]
8	-	61%	Project study	[51]
9	40–88%	93%	Project study	[51]

10	94%	33%	Project study	[51]
11	-	30%	Project study	[51]
12	-	65%	Project study	[51]

The overall performance range reported by the U.S. Environmental Protection Agency (EPA) (Project 3 in Table 6) is consistent with that reported by Cross et al. [4], who indicated TP removal efficiencies of 0–99% and TN removal efficiencies of 25–90%. This similarity suggests that both datasets may have been derived from the same underlying source.

The data compiled in Table 6 provide a more comprehensive assessment of nutrient removal performance. Reported TP removal efficiencies range from 40% to 99%, representing a narrower and more representative interval than those previously reported by the EPA [47] and Cross et al. [4]. In contrast, TN removal efficiencies exhibit substantially greater variability, ranging from 10% to 93%, thereby extending the performance range reported in earlier studies. This pronounced variability complicates direct comparison among studies and highlights the complexity of the mechanisms governing nitrogen removal.

The removal of TN and TP is controlled by numerous interacting factors, including the characteristics of the filter medium, effective grain size (defined as the sieve diameter through which 10% of the pre-weighed sample passes), porosity, infiltration depth, hydraulic loading conditions, pH, and temperature. Higher temperatures generally enhance nitrification, while short water application periods promote oxygen transfer and favor nitrification by maintaining aerobic conditions in the upper soil layers. In addition, the chemical form of nitrogen strongly influences treatment performance. Bhargava and Lakmini [20], for example, reported high nitrogen removal efficiencies in rapid-rate soil infiltration systems in California when the applied wastewater had not undergone prior nitrification, meaning that nitrogen was predominantly present in ammoniacal or ammonium forms.

Elimination of heavy metals

Heavy metals have become increasingly prevalent in aquatic environments as a consequence of anthropogenic activities. Industrial and municipal wastewater constitute the main sources of heavy metal contamination. The most frequently reported heavy metals include lead (Pb), zinc (Zn), mercury (Hg), nickel (Ni), cadmium (Cd), copper (Cu), chromium (Cr), arsenic (As), cobalt (Co), calcium (Ca), and manganese (Mn), which may occur in either dissolved form (free ions or complexes) or particulate form associated with suspended solids.

Unlike many organic pollutants, heavy metals are not biodegradable and can accumulate in living organisms, posing significant risks to ecosystems, wildlife, and human health through bioaccumulation and biomagnification [52]. Although conventional treatment technologies can achieve high removal efficiencies, their implementation is often associated with high capital and operational costs, particularly at large scale.

In constructed wetlands, heavy metal removal is achieved through a combination of physicochemical and biological mechanisms, including sedimentation, filtration, adsorption, precipitation, volatilization, plant uptake, and microbial transformations. The review by Zhang et al. [14] synthesized the findings of numerous studies investigating heavy metal removal in constructed wetlands. Table S1 (Supplementary Material) summarizes the removal efficiencies reported for arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn).

According to Zhang et al. [14], constructed wetlands generally achieve removal efficiencies below 50% for most heavy metals, with manganese exhibiting the highest reported average removal efficiency (49%).

In stabilization ponds and microalgae-based systems, heavy metal removal is primarily mediated by microalgae through phytoremediation processes, including biosorption and bioaccumulation. Mahapatra et al. [53] compiled data from numerous studies evaluating the heavy metal removal capacity of different microalgal species, and the reported removal efficiencies are summarized in Table S2 (Supplementary Material). Reported efficiencies vary widely depending on the metal, microalgal species, influent characteristics, and operating conditions. Consequently, the values presented in Table S2 should be interpreted as indicative examples rather than directly comparable performance indicators. Information regarding heavy metal removal by land treatment systems remains relatively limited. A report published by the U.S. Environmental Protection Agency (EPA) in 1981 describes the capacity of overland flow systems to remove metals through adsorption onto clay particles, precipitation as insoluble hydroxides, and the formation of organometallic complexes with soil organic matter [54]. Data from an overland flow system in Mississippi reported removal efficiencies of up to 80% for cadmium (Cd), nickel (Ni), copper (Cu), and zinc (Zn).

Overall, heavy metal removal in NBS results from multiple interacting mechanisms, including adsorption, precipitation as insoluble salts, plant uptake, and the settling of suspended solids. Differences in the physicochemical properties of individual metals, such as their affinity for adsorption, precipitation potential, and biological uptake, largely explain the variability in reported removal efficiencies [55,56]. Since heavy metals are not biodegradable, the reported removal efficiencies primarily reflect pollutant retention or transfer to the substrate, sediments, or plant biomass rather than degradation. Consequently, appropriate management of accumulated contaminants should be considered when evaluating the long-term sustainability of these systems.

Although the reported results are promising, the available evidence remains limited for several NBS and heavy metals. Additional studies covering a broader range of systems, operating conditions, and contaminants are needed to establish the overall effectiveness and long-term reliability of NBS for heavy metal removal.

Elimination of contaminants of emerging concern

Contaminants of emerging concern (CECs) are recently recognized chemical substances detected in natural waters and wastewater that may pose significant risks to ecosystems and human health [12]. This broad group includes pharmaceuticals and personal care products (PPCPs), antibiotics, pesticides, antiparasitic agents, detergents, cosmetic ingredients, and many other synthetic compounds [57].

The growing importance of these contaminants is reflected in recent regulatory developments. In particular, European Directive 2024/3019 is the first European legislation to explicitly address emerging contaminants in wastewater, introducing mandatory quaternary treatment by 2033 and establishing a minimum removal efficiency of 80% for selected compounds. These include pharmaceuticals such as carbamazepine, diclofenac, and venlafaxine, together with industrial chemicals such as benzotriazoles.

Conventional wastewater treatment plants were not designed to remove these micropollutants, resulting in incomplete removal and their continuous release into aquatic environments [58,59]. In this context, NBS have emerged as promising alternatives because they combine multiple physical, chemical, and biological removal mechanisms. Recent reviews indicate that constructed wetlands, microalgae-based systems, and hybrid configurations can achieve high removal efficiencies for a broad spectrum of emerging contaminants while maintaining relatively low operational costs [17].

Pharmaceuticals and personal care products are among the most extensively investigated CECs. Hijosa-Valsero et al. [60] compared seven constructed wetland configurations with a conventional activated sludge system and found that wetlands efficiently removed most of the target compounds, including ibuprofen, naproxen, salicylic acid, caffeine, and

methyl dihydrojasmonate, with removal efficiencies exceeding 80%. In contrast, the conventional system showed comparatively poor performance for compounds such as diclofenac and carbamazepine.

Similar findings were reported by Vymazal et al. [61], who observed removal efficiencies above 75% for paracetamol, caffeine, and furosemide, and above 50% for triclosan, ibuprofen, and clarithromycin. Verlicchi and Zambello [62] likewise highlighted the substantial removal of PPCPs across different constructed wetland configurations.

Waste stabilization ponds have also demonstrated strong performance for PPCP removal. K'oreje et al. [63] reported removal efficiencies exceeding 90% for approximately 70% of the investigated compounds, with some pollutants being removed more effectively than in conventional treatment systems.

These findings are consistent with recent reviews showing that constructed wetlands and microalgae-based systems can achieve removal efficiencies above 90% for several micropollutants, particularly when appropriate substrates, hydraulic conditions, and microbial communities are established [17,27].

Steroid hormones, widely used in pharmaceuticals and livestock production, are of particular environmental concern because of their endocrine-disrupting activity. Their removal in NBS is primarily governed by adsorption, biodegradation, photodegradation, and bioaccumulation [64]. A study evaluating a treatment train consisting of five constructed wetlands reported removal efficiencies of 40–60% for the individual units, whereas the overall system achieved up to 97% removal [58]. Comparable results have been reported for both constructed wetlands and high-rate algal ponds, with overall removal efficiencies exceeding 90% under favorable operating conditions [64]. These results highlight the importance of combining multiple biological treatment stages to maximize steroid hormone removal [17].

Pesticides, including herbicides, insecticides, fungicides, and bactericides, are another important group of emerging contaminants owing to their widespread agricultural use and potential ecological impacts. Constructed wetlands have demonstrated high removal efficiencies for many pesticides, with some studies reporting values approaching 100% for specific compounds [65–67]. Herbicides appear to be particularly well removed by these systems. Likewise, microalgae-based systems have shown considerable potential, with certain algal species achieving near-complete removal under optimized operating conditions [68–70]. Recent reviews further indicate that hybrid and bioengineered NBS can enhance pesticide removal through the combined action of adsorption, photodegradation, and microbial transformation processes [17].

Overall, the available evidence indicates that no single Nature-Based Solution consistently outperforms all others across every category of emerging contaminant. Constructed wetlands and microalgae-based systems generally exhibit high removal efficiencies for a wide range of micropollutants, although their performance remains strongly dependent on system configuration, operating conditions, and pollutant properties. The substantial variability reported among studies reflects the influence of factors such as influent composition, climatic conditions, hydraulic loading, and treatment design [17]. In addition, the dominant removal mechanisms—including adsorption onto substrates, microbial degradation, and photolytic processes—vary considerably among compounds, resulting in contaminant-specific treatment efficiencies.

Another emerging challenge is the occurrence of antibiotic-resistant bacteria and antibiotic resistance genes in treated wastewater. Recent studies indicate that constructed wetlands can substantially reduce these microbiological hazards, further supporting their potential role in advanced wastewater treatment [45].

Overall, NBS can achieve removal efficiencies comparable to, and in some cases exceeding, those of conventional treatment technologies for a range of emerging contami-

nants. Nevertheless, their performance remains highly site-specific, emphasizing the importance of appropriate system design, process optimization, and, where necessary, the integration of hybrid treatment configurations to ensure robust and reliable long-term performance.

3.3. Loading Rate

Loading rate is a key parameter for evaluating the treatment capacity of wastewater treatment systems, as it reflects the volume of wastewater that can be treated per unit area and time. In NBS, loading rates are generally much lower than in conventional treatment technologies, directly influencing both treatment capacity and land requirements, as consistently reported in studies of full-scale systems [9].

A fundamental trade-off exists between loading rate and treatment performance. Increasing the loading rate generally reduces hydraulic retention time, which may compromise pollutant removal efficiency, whereas lower loading rates enhance treatment performance at the expense of larger land requirements. This trade-off is particularly important in decentralized applications, where available land and treatment objectives must be carefully balanced. Recent studies have identified these interactions as a key consideration in the design and selection of NBS, often requiring compromises among treatment performance, land use, and operational simplicity [31].

To facilitate comparison, Table 7 summarizes the loading rates reported for the different NBS and conventional wastewater treatment technologies, highlighting the substantial differences in treatment capacity between these approaches.

Table 7. Loading rates of different NBS and conventional wastewater treatment technologies.

NBS	Loading Rate (m ³ /m ² /día)	References
Constructed wetlands	Vertical flow	0.1
	Horizontal flow	0.02–0.4
	Free water surface	0.026–0.13
	Floating	-
	Willow systems	0.002–0.004
Land treatment	Slow-rate soil infiltration	0.001–0.02
	Rapid-rate soil infiltration	0.02–0.3
	Overland flow	0.008–0.06
Stabilization ponds	Surface aerated flow	0.02–0.09
	Anaerobic	-
	Facultative	-
	Maturation	-
Microalgae	-	-
Typical conventional systems	10–50	Enterprise study [18]

Estimating the loading rates of conventional wastewater treatment technologies is challenging because their design is generally based on organic loading rates rather than surface-based hydraulic loading. In addition, published data on hydraulic loading rates are relatively scarce. Consequently, the values presented in Table 7 should be regarded as indicative and are intended primarily to illustrate orders of magnitude. Overall, conventional treatment technologies can accommodate hydraulic loading rates approximately 100 to 10,000 times greater than those of NBS. This substantial difference reflects their reliance on process intensification, including aeration, mechanical mixing, and other engineered processes that increase treatment capacity per unit area.

As shown in Table 7, constructed wetlands—excluding willow systems—and rapid-rate soil infiltration systems exhibit the highest loading rates among the NBS considered, exceeding $0.1 \text{ m}^3\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ [4,7]. These technologies are therefore better suited to situations where land availability is limited and relatively high treatment capacities are required. In particular, vertical-flow constructed wetlands and systems incorporating enhanced aeration generally achieve higher loading rates owing to improved oxygen transfer and more efficient biological treatment processes [9].

In contrast, willow systems and slow-rate soil infiltration systems operate at substantially lower loading rates because they do not produce a collected effluent [4]. In willow systems, treated wastewater is primarily removed through evapotranspiration and soil infiltration, both of which are inherently slow processes. Likewise, slow-rate soil infiltration systems rely on the gradual infiltration of wastewater into the soil profile without subsequent effluent collection, resulting in low surface-based hydraulic loading rates.

The analysis confirms that loading rate is a key factor governing the applicability of most NBS, as it directly influences both land requirements and system scalability. Technologies operating at low loading rates require extensive land areas and are therefore generally restricted to low-density settings. By contrast, systems with higher loading rates, such as rapid-rate soil infiltration systems and certain constructed wetland configurations, provide more compact treatment solutions but may require greater operational complexity or higher energy inputs. This trade-off highlights the importance of process intensification strategies that increase treatment capacity while maintaining satisfactory treatment performance [17].

Overall, loading rate is a decisive criterion in the selection of NBS. Although low loading rates may limit the applicability of many NBS in urban environments, they are often well suited to rural and peri-urban settings, where land availability is less restrictive. The strong influence of hydraulic loading conditions further emphasizes the need for site-specific design and integrated decision-making when selecting the most appropriate treatment technology.

3.4. Field Area Requirements

Land requirement is one of the most important factors determining the feasibility of NBS, particularly for decentralized wastewater treatment. Because these technologies rely on natural treatment processes and relatively long hydraulic retention times, they generally require substantially larger land areas than conventional wastewater treatment technologies, as consistently reported in recent reviews of full-scale systems [9,28].

This characteristic represents both a limitation and an advantage. On the one hand, large land requirements constrain the implementation of NBS in densely populated urban environments. On the other hand, in rural and peri-urban areas where land is more readily available, they enable cost-effective, low-energy treatment solutions that can be well integrated into the surrounding landscape. Recent studies further indicate that land availability is often the dominant factor influencing technology selection, frequently outweighing treatment performance and other technical considerations [31].

To facilitate comparison, Table 8 summarizes the land requirements of different NBS and conventional wastewater treatment technologies, highlighting the substantial differences in spatial demand between these approaches.

Table 8. Land requirements of different NBS and conventional wastewater treatment technologies.

NBS		Field Area Requirements (m ² /p.e.)	References
Constructed wetlands	Vertical flow	4	Global study [4]
	Horizontal flow	2	Global study [4]
	Free water surface	3–5	Global study [4]
	Floating	1.5	Case study [71]
	Willow systems	30–75	Global study [4]
Land treatment	Slow-rate soil infiltration	60–740	Global study [4]
	Rapid-rate soil infiltration	0.45–8.25	Global study [47]
	Overland flow	-	Global study [4]
Stabilization ponds	Surface aerated flow	1–5	Global study [4]
	Anaerobic	0.2	Global study [4]
	Facultative	1–3	Global study [4]
	Maturation	3–10	Global study [4]
	Microalgae	6–10	Global study [6]
Conventional systems		0.15–0.25	Global study [6]; Modelling study [72]

Conventional wastewater treatment technologies generally require substantially less land than most NBS. Among the NBS considered, willow systems and slow-rate soil infiltration systems exhibit the largest land requirements, typically requiring several tens of square meters per population equivalent (PE). By contrast, other constructed wetland configurations and rapid-rate soil infiltration systems require considerably smaller areas, with some reported values approaching those of conventional treatment technologies. Waste stabilization ponds also exhibit relatively low land requirements, generally below 10 m²·PE⁻¹. Anaerobic ponds require as little as 0.2 m²·PE⁻¹, making their spatial efficiency comparable to that of conventional systems [4]. These differences primarily reflect variations in system design, hydraulic loading rates, and treatment configuration [9].

The analysis confirms that land requirement is one of the main factors governing the applicability of NBS. Technologies such as slow-rate soil infiltration and willow systems require extensive land areas and are therefore primarily suited to low-density regions. Conversely, rapid-rate soil infiltration systems and certain constructed wetland configurations can achieve land requirements comparable to those of conventional treatment technologies. These differences illustrate the potential of process intensification strategies, such as enhanced aeration and hybrid treatment configurations, to reduce land requirements while maintaining treatment performance, albeit at the expense of greater operational complexity and, in some cases, higher energy demand [17].

Overall, land availability is a decisive criterion in the selection of NBS. Although their relatively large footprint may limit implementation in densely populated urban areas, it is generally compatible with rural and peri-urban settings, where land is more readily available. Consequently, land availability should be considered alongside treatment objectives, operational requirements, and local constraints when selecting the most appropriate NBS for decentralized wastewater treatment.

3.5. Energy Requirements

Energy consumption is a key indicator for assessing the sustainability and operational costs of wastewater treatment technologies. Compared with conventional systems, NBS generally require substantially lower energy inputs because they rely primarily on passive processes such as gravity-driven flow, microbial activity, and plant uptake. Consequently, they are typically associated with lower operational costs and reduced energy

demand [9,28]. Nevertheless, not all NBS operate under negligible energy requirements. Technologies such as microalgae-based systems and aerated waste stabilization ponds may require additional energy for mixing, aeration, or pumping. Recent studies have shown that energy demand depends strongly on system design and operating conditions, reflecting the trade-offs among treatment performance, land requirements, and operational inputs [31]. Thus, although NBS are generally regarded as low-energy technologies, their overall performance remains closely linked to design and operational choices.

To facilitate comparison, Table 9 summarizes the energy consumption of different NBS and conventional wastewater treatment technologies, highlighting the substantial reductions in energy demand achieved by most NBS. Relative energy savings were estimated using an activated sludge system with an energy consumption of $0.5 \text{ kWh}\cdot\text{m}^{-3}$ as the reference case, a representative value reported by Nogueira et al. [3] and Ación et al. [6]. These results are consistent with recent reviews showing that the lower energy demand of NBS is primarily attributable to their reliance on natural treatment processes rather than energy-intensive mechanical operations [9,17].

The reduction in energy demand achieved by NBS is substantial. For most technologies, energy consumption is negligible or very low. Even for systems requiring electrical inputs, such as microalgae-based technologies or installations requiring wastewater pumping and flow distribution (e.g., some willow systems), energy savings generally exceed 40% relative to conventional treatment technologies. This reduction is particularly advantageous in decentralized applications, where low energy demand contributes to lower operating costs, greater system resilience, and improved long-term sustainability.

Table 9. Energy consumption of different NBS and conventional wastewater treatment technologies.

NBS	Energy Consumption (kWh/m^3)	Relative Difference with Conventional Systems (%)	References
Activated sludge systems	0.22–0.82	-	Global studies [5,6]
Constructed wetlands	Vertical flow	0–0.25	50–100% Global studies [5,6]
	Horizontal flow	0–0.25	50–100% Global studies [5,6]
	Free water surface	0–0.25	50–100% Global studies [5,6]
	Floating	0	100% Global studies [5,6]
	Willow systems	0.16–0.23	40–68% Global study [4]
Land treatment	Slow rate soil infiltration	0.04	92% Global study [5]
	Rapid-rate soil infiltration	0	100% Global study [5]
	Overland flow	0	100% Global study [5]
	Surface aerated flow	-	-
Stabilization ponds	Anaerobic	0.04	92% Global study [5]
	Facultative	0.04	92% Global study [5]
	Maturation	0.04	92% Global study [5]
Microalgae	0.3	40%	Experimental study [36]

The analysis clearly demonstrates that NBS offer a substantial advantage in terms of energy consumption, with many technologies requiring little or no external energy input.

This represents a major benefit for decentralized wastewater treatment, particularly in locations where access to reliable energy infrastructure is limited.

Nevertheless, energy demand varies considerably among NBS. Technologies requiring aeration or active process control, such as microalgae-based systems, generally exhibit higher energy consumption than fully passive treatment systems, thereby reducing part of their energy advantage. Likewise, advanced or hybrid configurations, including microalgae-based and bioelectrochemical systems, may require additional energy inputs to achieve enhanced removal of specific contaminants [17].

Overall, the low energy demand of most NBS further supports their potential as sustainable alternatives to conventional wastewater treatment technologies, especially in rural and resource-limited settings. At the same time, the variability in energy consumption among different technologies highlights the importance of context-specific system design and careful technology selection to balance treatment performance, resource use, and operational requirements [4–6,36].

3.6. Conclusion of the Technical Study

The three NBS exhibiting the highest pollutant removal performance in Figure S2—willow systems, slow-rate soil infiltration systems, and microalgae-based systems—display contrasting performance across the other evaluation criteria. Willow systems and slow-rate soil infiltration systems operate at loading rates that are one to two orders of magnitude lower than those of the highest-capacity NBS, namely vertical-flow constructed wetlands. Consequently, they also require substantially larger land areas, typically one to two orders of magnitude greater than those of the most land-efficient NBS. By contrast, microalgae-based systems combine high pollutant removal efficiencies with relatively low land requirements. Although these three technologies exhibit the highest energy demand among the NBS evaluated—particularly microalgae-based and slow-rate soil infiltration systems—their overall energy consumption remains low compared with that of conventional wastewater treatment technologies.

Overall, the results demonstrate that no single Nature-Based Solution performs optimally across all evaluation criteria. Rather, each technology presents specific strengths and limitations, reflecting the inherent trade-offs among treatment performance, loading capacity, land requirement, and energy demand. When appropriately selected and adapted to site-specific conditions, individual NBS or integrated treatment configurations can achieve treatment performance comparable to that of conventional wastewater treatment technologies.

4. Economic Evaluation of Nature-Based Solutions for Decentralized Wastewater Treatment

The available evidence indicates that NBS are considerably more cost-effective than conventional activated sludge systems. Reported construction costs are typically 66–96% lower, largely owing to the reduced need for complex infrastructure, mechanical equipment, and energy-intensive treatment processes.

These economic advantages, however, should be interpreted in the context of the specific requirements of each application. Although NBS provide clear cost benefits in rural and decentralized settings, their greater land requirements and lower treatment capacity may reduce their economic competitiveness in densely populated or land-constrained environments.

Su et al. [5] conducted a comparative assessment of the construction costs of several wastewater treatment technologies, including activated sludge systems and selected NBS. In general, NBS require fewer construction materials and involve simpler installation pro-

cesses, contributing to their lower capital costs. To facilitate comparison, Table 10 summarizes the reported construction costs of selected NBS together with their relative cost difference compared with conventional activated sludge systems, highlighting the substantial economic savings associated with these technologies.

Table 10. Construction costs of different NBS and their relative difference compared with conventional activated sludge systems [5].

Treatment System	Construction Cost (€·PE ⁻¹)	Relative Difference with Activated Sludge System (Average of 79.4 €·PE ⁻¹)
Activated sludge	53–106	
Constructed wetlands	3–13	84–96%
Slow-rate soil infiltration	9–18	77–89%
Land treatment Rapid-rate soil infiltration	4–13	84–94%
Overland flow	4–13	84–94%
Stabilization ponds	9–27	66–89%

The construction costs of NBS are substantially lower than those of conventional activated sludge systems, highlighting their potential as cost-effective alternatives, particularly for decentralized wastewater treatment and resource-limited settings. Reported capital cost reductions range from 66% to 96%, indicating that an NBS designed to treat an equivalent wastewater flow can be approximately three to twenty-five times less expensive to construct than a conventional activated sludge system.

This economic advantage makes NBS particularly attractive where financial resources are limited. However, cost-effectiveness cannot be evaluated independently of other design constraints, particularly land availability and treatment capacity. In situations where land is scarce or high treatment capacities are required, the apparent economic benefits of NBS may be partially offset by their larger land requirements and lower hydraulic loading rates.

Regarding operational costs, these may include maintenance, land use, monitoring, energy consumption, human resources, media replacement, desludging, repair works, plant harvesting, and other routine operational activities [24,71]. In addition, end-of-life costs associated with infrastructure rehabilitation or substrate replacement may also contribute to the overall life-cycle cost of some NBS, although these aspects are rarely reported in the literature. Based on the current state of knowledge, it remains difficult to establish a consistent distribution of these cost components across different NBS because available economic assessments are highly heterogeneous and strongly influenced by local conditions. For example, land acquisition may represent a major cost component in densely populated areas, whereas labour, energy consumption, or maintenance requirements may dominate operational costs in other contexts. Consequently, the economic viability of NBS should be assessed considering the entire life cycle rather than construction costs alone.

Overall, NBS provide a cost-effective solution under appropriate conditions, but their economic viability remains strongly dependent on site-specific factors. Consequently, economic assessments should be integrated with technical, environmental, and spatial considerations to support informed technology selection.

5. Environmental Evaluation of Nature-Based Solutions for Decentralized Wastewater Treatment

The environmental performance of wastewater treatment technologies is a key component of their overall sustainability. Compared with conventional treatment systems, NBS provide important environmental advantages, primarily because of their low energy demand, reduced chemical requirements, and integration with natural ecosystems.

Assessing the environmental performance of NBS, however, is inherently complex. Their overall sustainability depends not only on treatment efficiency but also on interactions with surrounding ecosystems, resource recovery potential, and long-term system performance. Consequently, a comprehensive evaluation requires multiple complementary assessment approaches. In this review, environmental performance is examined from two perspectives: (i) the ecosystem services provided by NBS, highlighting their ecological and societal benefits, and (ii) life cycle assessment (LCA), which enables a quantitative evaluation of environmental impacts throughout the system life cycle.

5.1. Ecosystem Services

The concept of ecosystem services refers to the benefits that humans obtain directly or indirectly from ecosystems [73]. In the context of NBS, this concept is particularly relevant because these technologies create, restore, or utilize natural habitats that provide multiple ecological and societal benefits in addition to wastewater treatment.

Ecosystem services are commonly classified into four categories:

- Provisioning services: These comprise the tangible goods and resources supplied by ecosystems [74]. In NBS, they include production, harvesting, drying, and utilization of plant biomass for industrial or energy purposes. In addition, treated wastewater can be reused for agricultural irrigation or industrial applications.
- Regulating services: These arise from ecosystem processes that regulate environmental conditions and maintain ecosystem functioning [74]. Wastewater treatment itself is a regulating service because it reduces pollutant loads released into the environment. Furthermore, vegetation contributes to climate regulation, soil stabilization, erosion control, and sediment retention.
- Cultural services: These encompass the non-material benefits derived from interactions between people and ecosystems [74]. Because many NBS are designed as open, vegetated, and multifunctional spaces, they can enhance the visual quality of urban and rural landscapes while providing opportunities for recreation, environmental education, and public engagement.
- Supporting services: These include the ecological processes that sustain the provision of all other ecosystem services, such as habitat formation, nutrient cycling, and primary production. Within NBS, the creation of natural habitats provides refuge for residents and migratory wildlife while supporting nutrient and water cycling. For example, Cross et al. [4] described a slow-rate soil infiltration system in Michigan (USA), where the treatment pond functions as habitat for aquatic birds and provides refuge for migratory species during the summer.

The ecosystem services framework highlights the multiple environmental and societal benefits associated with the implementation of NBS, extending well beyond wastewater treatment alone. This qualitative perspective complements LCA, which provides a more quantitative and systematic evaluation of the environmental performance of these systems.

5.2. Life Cycle Assessments of the NBS

LCA is a standardized methodology defined by the International Organization for Standardization (ISO) through the ISO 14040 and ISO 14044 standards [75, 76, 77]. It provides a systematic framework for evaluating the environmental impacts associated with all stages of the life cycle of a product, process, or system, from raw material extraction to final disposal [78]. In the field of wastewater treatment, LCA is widely used to compare the environmental performance of conventional and NBS.

Machado et al. [79] compared the environmental performance of three wastewater treatment systems: a constructed wetland, a slow-rate soil infiltration system, and an activated sludge system. The assessment was based on six environmental impact categories:

1. Abiotic Depletion Potential (ADP);
2. Global Warming Potential (GWP);
3. Ozone Layer Depletion Potential (OLDP);
4. Photochemical Oxidant Creation Potential (POCP);
5. Acidification Potential (AP); and
6. Eutrophication Potential (EP).

Figure 3 compares the values of these six environmental indicators for the three treatment systems using population equivalent (PE) as the functional unit.

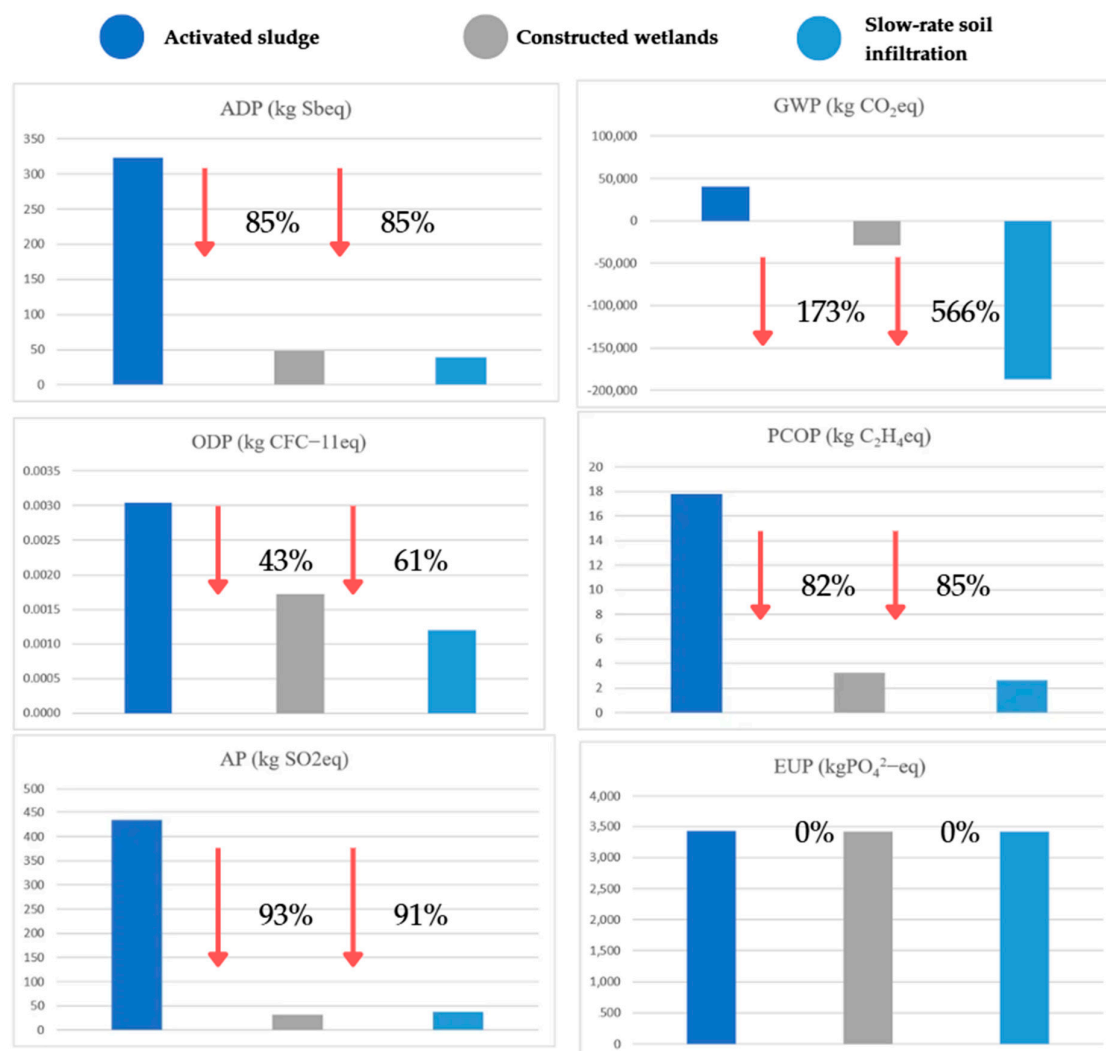


Figure 3. Comparison of six environmental impact indicators for three wastewater treatment systems based on the life cycle assessment by Machado et al. [79].

The results clearly indicate that the two NBS exhibit lower environmental impacts than the activated sludge system across most of the evaluated impact categories. In particular, the slow-rate soil infiltration system displays a negative global warming potential, reaching $-187 \text{ t CO}_2\text{-eq}$ per population equivalent (PE), reflecting its substantial potential for carbon sequestration and greenhouse gas mitigation.

For the remaining impact categories, the constructed wetland and the slow-rate soil infiltration system consistently exhibit lower environmental impacts than the activated sludge system. The only exception is eutrophication potential, for which the three systems show comparable results.

These findings are consistent with those reported in previous LCA studies. Tangsubkul et al. [80] compared three wastewater treatment technologies—continuous micro-filtration, a membrane bioreactor, and a waste stabilization pond—across six environmental impact categories, including global warming, eutrophication, human toxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, and salinization. Their results identified the stabilization pond as the technology with the lowest overall environmental impacts.

Similarly, Nogueira et al. [3] compared a constructed wetland, a rapid-rate soil infiltration system, and an activated sludge system using three LCA impact categories: abiotic depletion potential, global warming potential, and acidification potential. In all cases, the activated sludge system exhibited the highest environmental impacts.

Nevertheless, contrasting results have also been reported. Lopsik [81] compared a constructed wetland with an activated sludge system and found that the wetland exhibited higher impacts for several categories, including global warming potential, human toxicity, terrestrial ecotoxicity, and acidification. The author attributed these results primarily to the high energy demand associated with the production of the expanded clay lightweight aggregate used as the wetland substrate.

These contrasting findings illustrate that LCA results are highly dependent on system configuration, material selection, and the assumptions adopted in the assessment. Consequently, comprehensive environmental evaluations should consider the contribution of each life cycle stage in order to identify the processes responsible for the overall environmental impacts.

5.3. Life Cycle Assessment of Each Stage of Life of NBS

The life cycle stages responsible for the greatest environmental impacts vary considerably depending on the treatment technology. Machado et al. [79] analyzed the contribution of the construction and installation, operation and maintenance, and decommissioning and end-of-life phases to the overall environmental impacts of both a constructed wetland and a slow-rate soil infiltration system. The following impact categories were evaluated:

1. Abiotic Depletion Potential (ADP);
2. Global Warming Potential (GWP);
3. Ozone Depletion Potential (ODP);
4. Photochemical Ozone Creation Potential (POCP);
5. Acidification Potential (AP); and
6. Eutrophication Potential (EP).

Figures 4 and 5 illustrate the contribution of each life cycle phase to the six environmental impact categories for the slow-rate soil infiltration system and the constructed wetland, respectively.

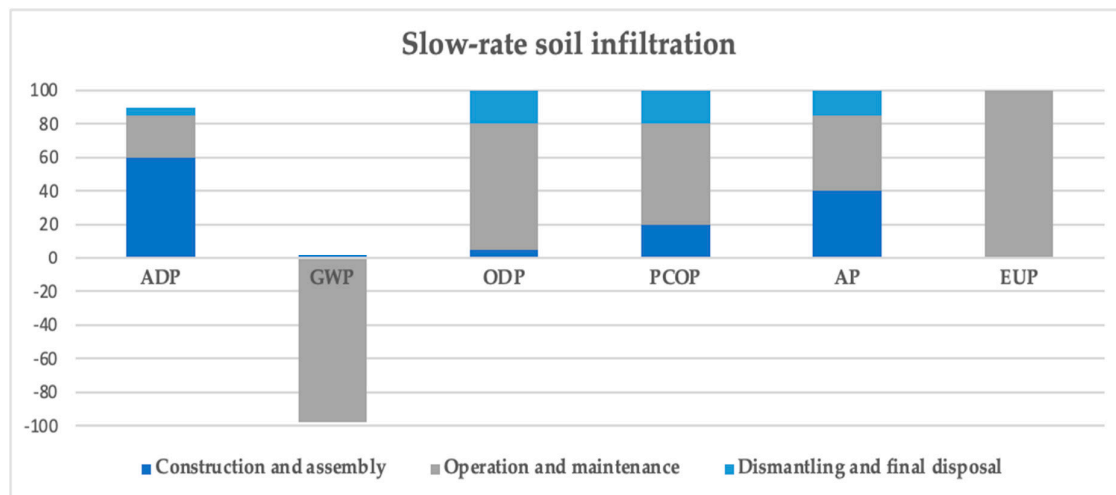


Figure 4. Distribution of environmental impacts across the life cycle stages of a slow-rate soil infiltration system [79].

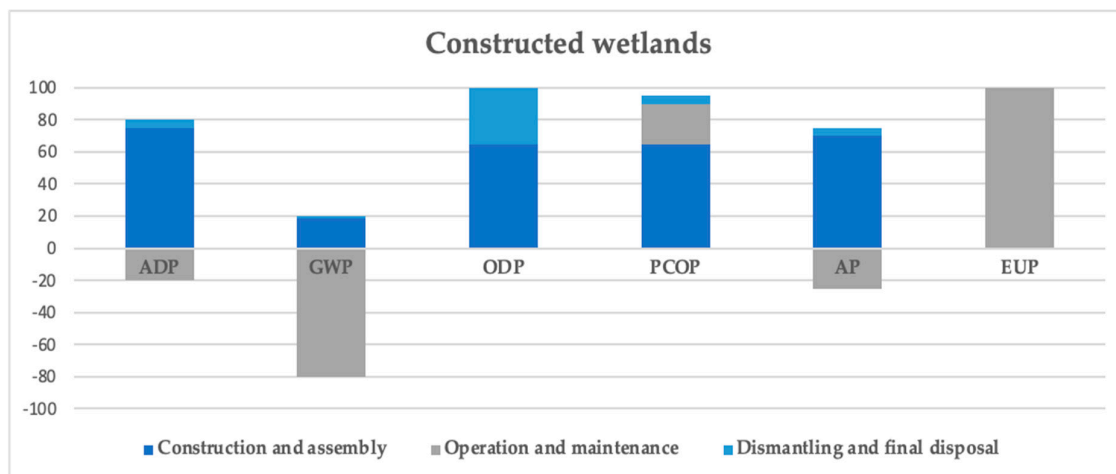


Figure 5. Distribution of the six environmental impact categories across the life cycle stages of a constructed wetland [79].

In both systems, the decommissioning and end-of-life phase contributed the least to the overall environmental impacts.

For the slow-rate soil infiltration system, the operation and maintenance phase was the dominant contributor to most impact categories. The only exception was abiotic depletion potential, for which the construction and installation phase represented the largest environmental burden.

By contrast, the construction and installation phase was the main contributor to four impact categories for the constructed wetland: ozone depletion potential, abiotic depletion potential, photochemical ozone creation potential, and acidification potential.

For waste stabilization ponds, Tangsubkul et al. [80] provided the data used to generate Figure 6, which illustrates the contribution of the different life cycle stages to six environmental impact categories. The life cycle was divided into four phases: construction, energy consumption during operation, effluent reuse (including methane emissions from the pond), and the use or disposal of treated sludge. The impact categories evaluated were:

1. Global Warming Potential (GWP);
2. Eutrophication Potential (EP);

3. Human Toxicity Potential (HTP);
4. Freshwater Aquatic Ecotoxicity Potential (FAETP);
5. Marine Aquatic Ecotoxicity Potential (MAETP); and
6. Terrestrial Ecotoxicity Potential (TETP).

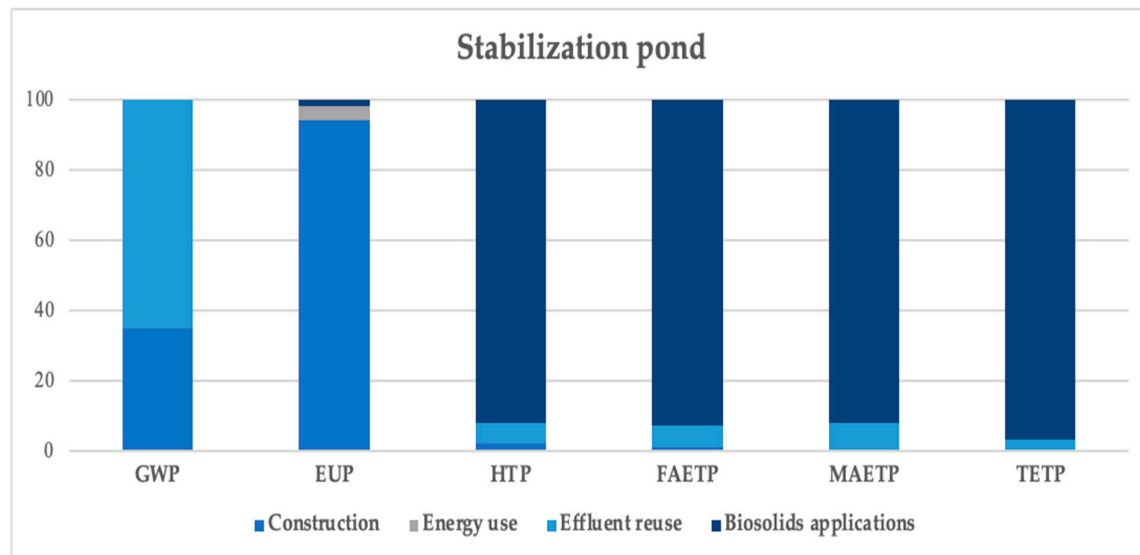


Figure 6. Distribution of the six environmental impact categories across the life cycle stages of a waste stabilization pond [80].

The results indicate that most toxicity-related impacts—including human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), and terrestrial ecotoxicity potential (TETP)—are primarily associated with the use or disposal of treated sludge.

Global warming potential is dominated by the effluent reuse stage, mainly because of methane emissions from the waste stabilization pond. In contrast, the construction phase accounts for approximately 95% of the eutrophication potential, indicating that this stage represents the principal environmental burden for this impact category.

Overall, although energy consumption contributes to the environmental impacts of waste stabilization ponds, other life cycle stages—particularly construction and treated sludge management—generally have a greater influence on the overall environmental performance of the system.

6. Recommendation for Social Acceptance and Local Implementation

The successful implementation of NBS for decentralized wastewater treatment depends not only on their technical, economic, and environmental performance but also on social acceptance and effective institutional support. In many cases, the long-term sustainability of these systems is strongly influenced by stakeholder engagement, community participation, and appropriate governance arrangements.

Unlike conventional wastewater treatment technologies, NBS are closely integrated into local environments and communities, making social and institutional factors critical determinants of their long-term success. Consequently, understanding and addressing these dimensions is essential to ensure successful implementation, effective operation, and long-term sustainability.

Sections 6.1 and 6.2. provide a practical framework for addressing the main social and governance aspects associated with the implementation of NBS, with particular emphasis on promoting public acceptance and facilitating successful local deployment.

6.1. Indicators to Evaluate Social Impacts

Evaluating the social impacts of NBS is essential to ensure their long-term acceptance, sustainability, and positive contribution to local communities. These impacts encompass changes in employment, community well-being, the use of public spaces, and public perceptions associated with the implementation of decentralized wastewater treatment systems. This subsection presents a set of indicators that can be used to assess these social dimensions, organized into categories representing the main areas of potential benefit. Although not exhaustive, these indicators provide a structured framework for identifying, monitoring, and evaluating the social outcomes of NBS projects, thereby supporting informed decision-making and stakeholder engagement.

Figure 7 summarizes the proposed social indicators, grouped into three categories:

1. Worker-related indicators: The implementation of NBS can generate employment opportunities during both the construction and operation phases. This category includes indicators associated with job creation and local employment.
2. Community-related indicators: These indicators assess how the implementation of NBS influences the quality of life, well-being, and social acceptance of local communities.
3. Indicators related to shared and multifunctional spaces: Based on the social benefits reported by Cross et al. [4], these indicators highlight the potential of NBS to create accessible green spaces that encourage social interaction, recreation, environmental education, and community cohesion, while potentially increasing the attractiveness of the area for visitors and tourism.

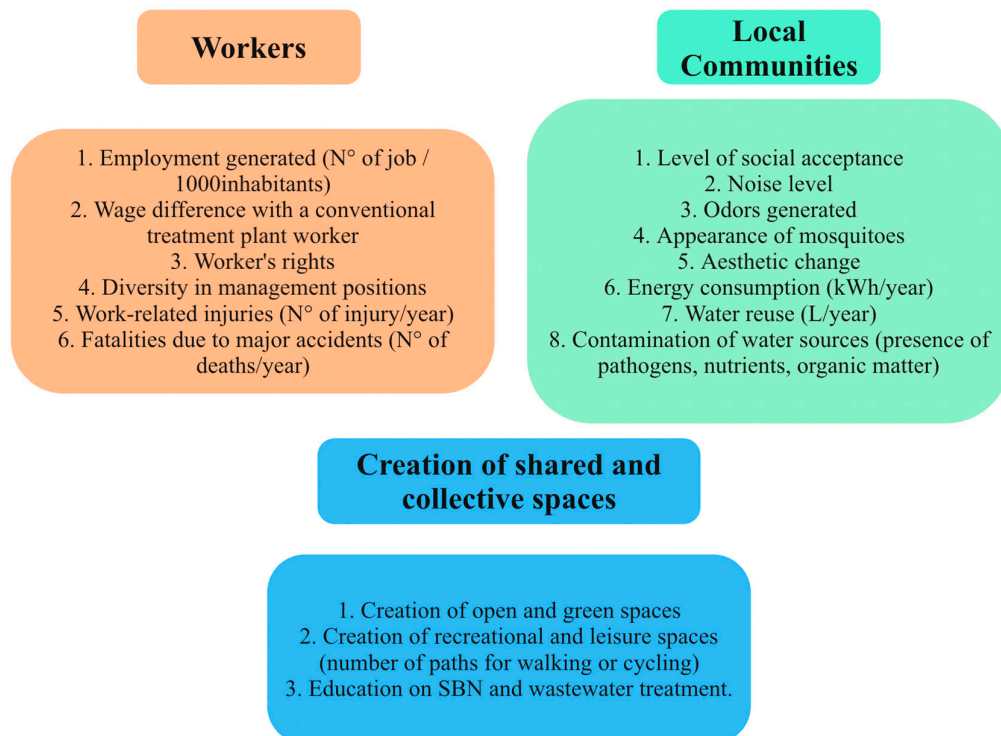


Figure 7. Indicators for evaluating the social impacts of NBS [4,82,83].

Although not exhaustive, this set of indicators provides a structured framework for identifying and assessing the main social dimensions associated with the implementation of NBS. Some indicators are expressed as quantitative measures (units shown in paren-

theses), whereas others require qualitative assessment through stakeholder surveys or must be adapted to the specific local context.

These indicators are intended as a conceptual framework and therefore provide only a partial assessment of the social impacts associated with NBS. To promote social acceptance and maximize benefits for local communities, their application should be complemented by environmental governance approaches that actively engage stakeholders throughout the planning, implementation, operation, and long-term management of the project.

6.2. Recommendations to Ensure the Durability of the Project and Strengthen Its Local Implementation

The long-term success and sustainability of NBS depend not only on their technical performance but also on strategies that promote strong local integration and community ownership. These strategies are closely aligned with the principles of environmental governance, which seek to address the social, economic, and political dimensions of environmental management through participatory, multi-level, and collaborative decision-making processes [84]. The growing body of literature on stakeholder engagement in NBS implementation consistently supports approaches based on these governance principles.

Successful implementation requires the active involvement of all relevant stakeholders—including local communities, public authorities, and technical practitioners—from the planning stage through operation and long-term maintenance. This section presents three practical recommendations to enhance project durability and strengthen local integration, focusing on participatory planning, capacity building, institutional support, and long-term monitoring. By adopting these measures, NBS projects are more likely to deliver lasting environmental, social, and economic benefits while fostering community ownership and long-term stewardship.

6.2.1. Understanding Local Acceptance

Establishing direct engagement with local communities is a fundamental step in promoting the acceptance of NBS. Early stakeholder consultation enables project developers to identify the most appropriate treatment technology while ensuring that the selected solution reflects local needs, expectations, and priorities. Surveys, interviews, and other participatory approaches are commonly used to collect information on the following aspects:

- **Motivations for wastewater treatment:** Communities may support wastewater treatment projects because of their environmental benefits, opportunities for water reuse, or expected improvements in public health. For example, in Bayawan (Philippines), residents primarily perceived benefits related to ecosystem regulation services, particularly wastewater treatment [85]. Similarly, in Costa Rica, interviews conducted prior to the implementation of a Biojardinera system showed that 77% of respondents supported the reuse of treated greywater for irrigation, recognizing its potential to improve local environmental conditions [86]. These examples suggest that the prospect of improving wastewater management can itself be a strong driver for the adoption of NBS.
- **Willingness to pay:** Understanding the willingness of local stakeholders to contribute financially is essential for designing appropriate funding mechanisms. In some contexts, farmers are willing to invest in wastewater treatment regardless of the quality of the treated effluent because of the need for irrigation water [87]. In contrast, other communities oppose financing such projects through local taxation [88]. For example, surveys conducted in Costa Rica evaluated the willingness of residents to contribute financially to greywater treatment before the implementation of an NBS [86]. Such

information is critical because financial support from local communities cannot be assumed and may influence both technology selection and project financing.

- **Impacts on tourism:** In tourism-dependent regions, wastewater treatment projects may influence visitors' perceptions and local economic activity. In Thailand, 87% of surveyed tourists expressed willingness to pay for improved wastewater treatment, whereas local residents were concerned that poorly managed facilities could negatively affect tourism [4]. In these contexts, tourism can become both a motivation for improving wastewater management and a potential source of long-term financial support for system operation and maintenance.
- **Perceived limitations:** Potential nuisances, including odors, mosquitoes, and visual impacts, may influence public acceptance. Although negative perceptions often increase with proximity to treatment facilities, residents living near constructed wetlands may also recognize aesthetic and environmental benefits [88]. Addressing these concerns at an early stage through transparent communication, dialogue with local communities, and the presentation of successful case studies can substantially improve social acceptance.

Social and cultural characteristics should also be carefully considered during project planning. In India, for example, social stratification influenced perceptions of constructed wetlands, with some communities valuing them primarily as irrigation infrastructure rather than as measures for drought mitigation, while caste-related stigmatization affected participation in project implementation [89]. Consequently, project teams should actively involve local organizations or institutions that possess a thorough understanding of the social and cultural context and can facilitate effective community engagement.

Figure 8 summarizes the main community concerns together with practical actions to enhance social acceptance during the three main phases of project development: before installation, during construction, and throughout system operation.

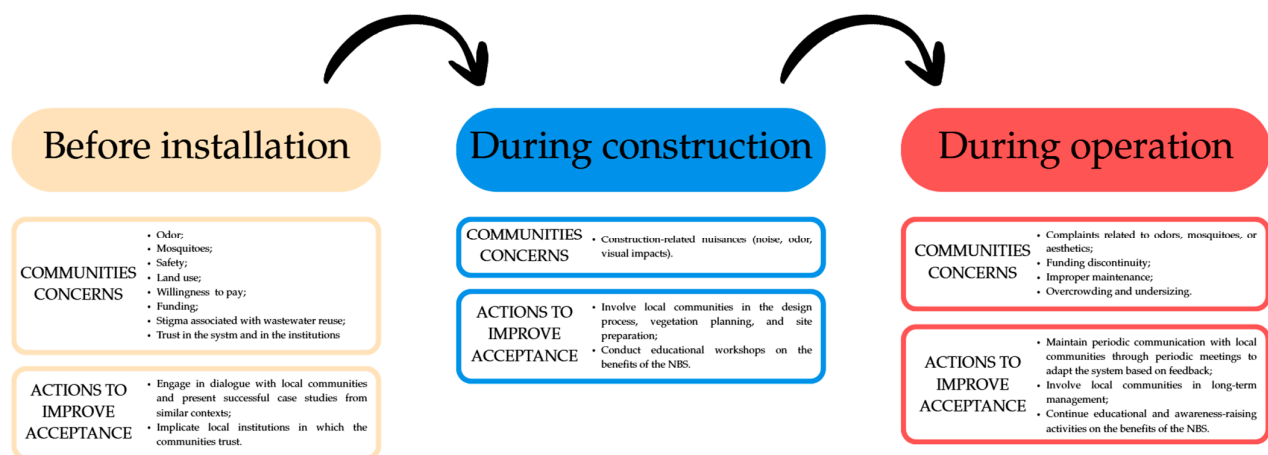


Figure 8. Framework for promoting social acceptance throughout the different stages of an NBS project.

6.2.2. Engaging Communities Throughout the Project

Continuous stakeholder engagement and public participation throughout the planning, implementation, operation, and maintenance phases are essential for the successful implementation of NBS. Sustained engagement enables local communities to better understand the objectives and benefits of the project, thereby increasing public support and reducing the risk of project abandonment or interruptions in long-term funding. Several studies have shown that insufficient community involvement has contributed to the fail-

ure of NBS projects [89,90]. Without sustained public support, financial and institutional resources may be redirected toward competing priorities [91].

Maintaining stakeholder engagement requires context-specific participatory approaches. Surveys can be used to monitor public perceptions, while regular community meetings provide opportunities to discuss operational issues and communicate project progress, performance, and benefits [88]. In Mexico, a constructed wetland was managed through a community-based approach in which local residents participated in system design, site preparation, vegetation planting, and educational activities [90]. Similarly, in Costa Rica, community members were involved in selecting the plant species through participatory interviews conducted before implementation [86].

6.2.3. Building Multi-Actor Networks for Sustainability

The long-term sustainability of NBS also depends on establishing a robust network of stakeholders capable of supporting their implementation and continued operation [84]. Such networks may include academic institutions, government agencies, local authorities, civil society organizations, and private-sector actors. Together, these stakeholders provide technical expertise, institutional support, financial resources, and governance mechanisms that contribute to the long-term viability of NBS while reducing the risk of project abandonment.

Monzón-Reyes et al. [90] proposed a governance model based on three principal actors: the academic sector, government institutions, and the local community, with the latter representing the central component of the network. Within this framework, local communities play an active role in project implementation and management, whereas the other stakeholders provide technical assistance, institutional support, and capacity building. Conversely, insufficient governmental involvement has been identified as a major factor contributing to project failure [90,91]. National consultation processes involving government agencies, civil society organizations, academic institutions, and private-sector representatives have therefore been recommended to strengthen implementation, coordination, and institutional support [85]. Public authorities can further facilitate NBS deployment through appropriate legislation, technical guidelines, public policies, and implementation frameworks.

In addition, strengthening local laboratory capacity and training specialists in wastewater monitoring are essential to ensure continuous performance assessment, adaptive management, and the long-term reliability of NBS.

7. Decision Guide

This framework has two main objectives:

- To provide a practical decision-support tool for selecting the Nature-Based Solution NBS that best matches the characteristics and constraints of a given context.
- To integrate the technical, environmental, economic, and social dimensions evaluated in Sections 3–6 into a comprehensive decision-making framework, drawing on the technical, environmental, and economic assessments (Sections 3–5) together with the social recommendations presented in Section 6.

Figure 9 presents a decision-support framework that summarizes the main actions to be undertaken across the four evaluation dimensions—technical, social, economic, and environmental—during the three principal stages of project development:

1. Requirements definition;
2. Development of a multi-stakeholder network; and
3. Final selection of the Nature-Based Solution.

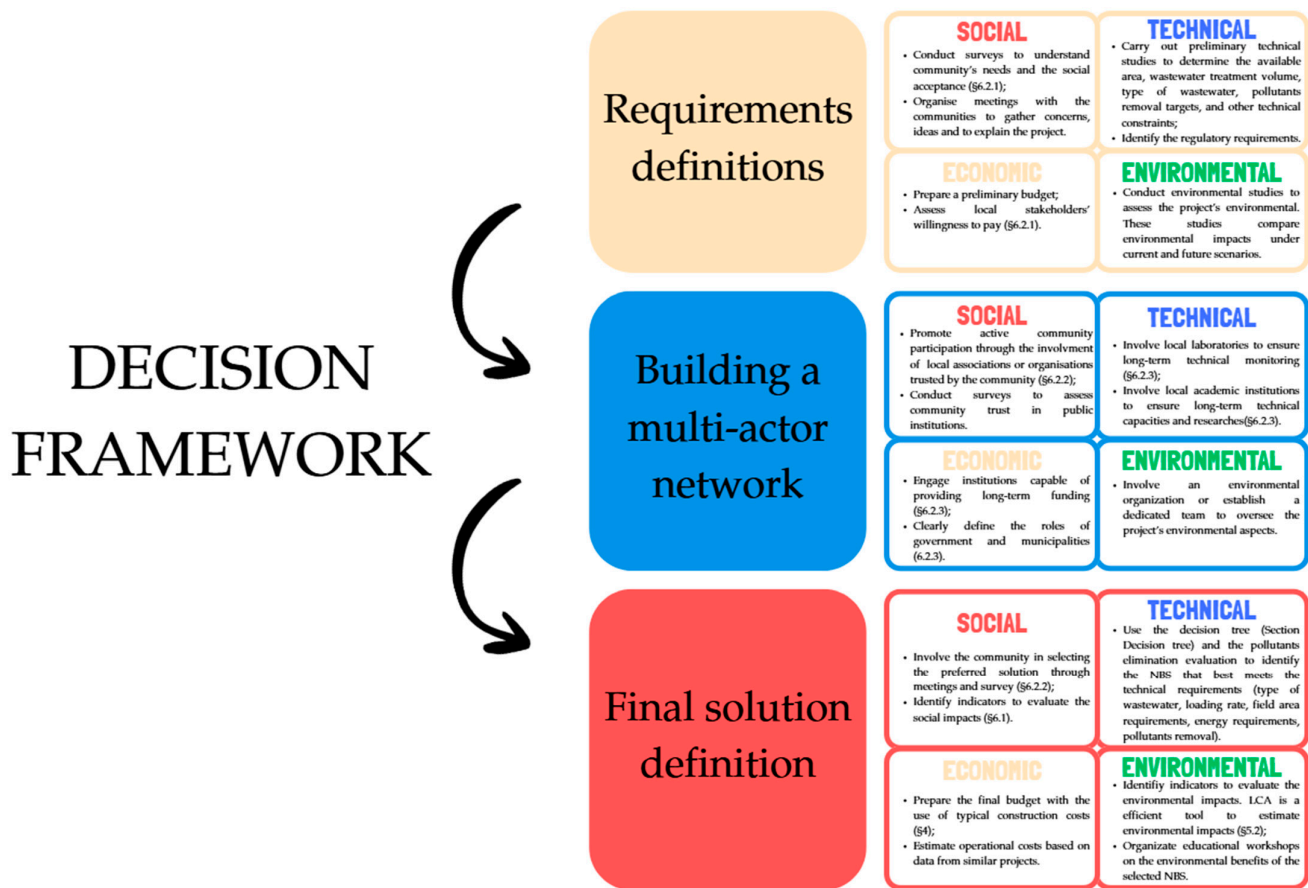


Figure 9. Decision-support framework for the selection and implementation of NBS.

It is important to emphasize that the four evaluation dimensions considered at each stage—social, technical, environmental, and economic—should not be assessed independently but rather as part of an iterative and integrated decision-making process.

During the requirements definition stage, preliminary technical assessments provide the basis for estimating project costs and defining the initial system configuration. At the same time, these technical assessments should incorporate the needs and expectations identified through stakeholder engagement, as well as the findings of preliminary environmental evaluations.

Similarly, the establishment of a multi-stakeholder network requires coordination among local organizations, academic institutions, environmental organizations, public authorities, and municipalities. The effectiveness of this collaborative network depends on the active participation and support of all relevant stakeholders.

Ultimately, the final selection of the NBS should result from the integrated assessment of all four dimensions. The preferred alternative should therefore be selected not only on the basis of its technical performance, economic feasibility, and environmental performance, but also considering community needs, stakeholder preferences, and long-term governance requirements. In parallel, appropriate social and environmental indicators should be defined at the outset of the project to support continuous monitoring and evaluation throughout implementation and operation.

Decision Tree

To complement the decision-support framework, Figure 10 presents a decision tree designed to facilitate the selection of the most appropriate Nature-Based Solution NBS

according to site characteristics and key design criteria. The decision tree is based on the results of the technical assessment presented in Section 3 and is intended as a conceptual decision-support tool for the preliminary selection of NBS. It provides an initial screening based on the technical evidence synthesized in this review rather than a prescriptive design methodology. Final technology selection should also consider site-specific treatment objectives, regulatory requirements, climatic conditions, life-cycle costs, operation and maintenance capacity, residual management, and social acceptance. Future developments could further strengthen this tool by integrating these additional criteria into a more comprehensive decision-support framework.

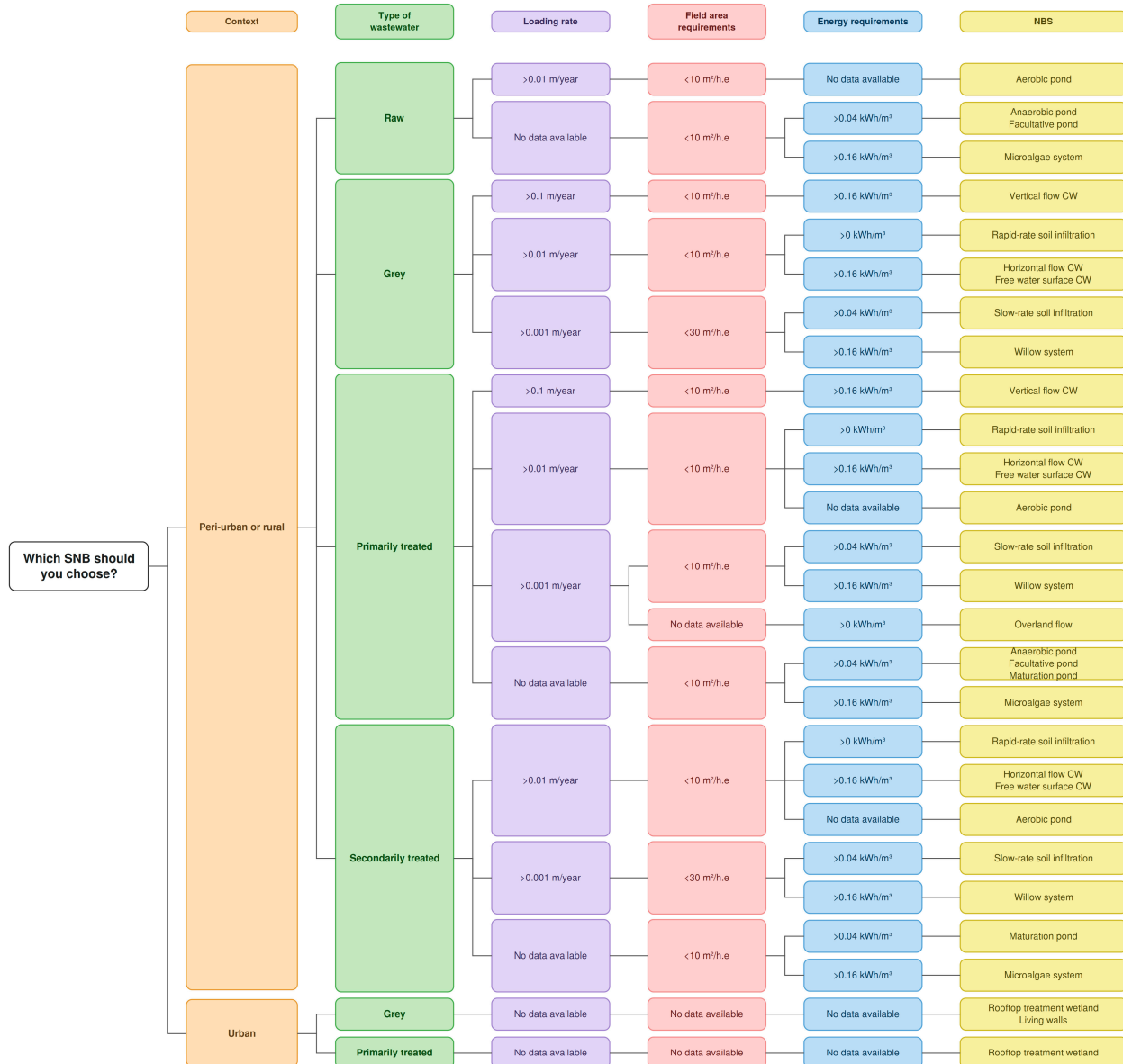


Figure 10. Decision tree for selecting the most appropriate NBS according to site conditions.

Five criteria are considered to guide the selection of the most appropriate NBS:

- Territorial context: urban, peri-urban, or rural.
- Wastewater type: raw wastewater, greywater, primary-treated wastewater, or secondary-treated wastewater.

- Hydraulic loading rate, classified according to the representative operating ranges identified in the reviewed literature.
- Land requirements, classified according to representative area demands reported for each NBS.
- Energy requirements, classified according to the representative energy consumption ranges reported in the literature.

The threshold values used in the decision tree were derived from the ranges of hydraulic loading rates, land requirements, and operating conditions most frequently reported in the literature reviewed in Section 3. These thresholds should therefore be interpreted as indicative values intended to support preliminary screening rather than as universally applicable design criteria.

When one or more decision variables are unavailable or uncertain, the decision tree should be used as a preliminary screening tool only. In such cases, alternative NBS identified through adjacent decision pathways should be further evaluated using site-specific technical, economic, environmental, and social criteria. Where data are indicated as unavailable, this means that no relevant information has been reported at the time of writing this review, and readers are encouraged to consult more recent literature where appropriate.

The decision tree is intended as a preliminary screening tool and may identify more than one suitable NBS for a given set of site conditions. This reflects the findings of the present review, which show that several technologies often exhibit comparable technical performance under similar operating conditions. Therefore, when multiple alternatives are identified, the final selection should be based on additional site-specific criteria such as treatment objectives, regulatory requirements, climatic conditions, life-cycle costs, operation and maintenance capacity, residual management, environmental impacts, and social acceptance.

The analysis demonstrates that social acceptance and effective governance are critical determinants of the successful implementation of NBS. Projects that actively engage local communities and other stakeholders from the earliest planning stages are more likely to achieve long-term sustainability, operational reliability, and continued institutional support.

Nevertheless, social dimensions are inherently context-specific and often difficult to quantify, limiting their direct integration into conventional decision-making frameworks. This highlights the need for flexible governance approaches and participatory processes that can be adapted to local environmental, social, and institutional conditions.

More broadly, the effectiveness of NBS depends not only on their technical performance but also on their successful integration into the social and institutional context in which they are implemented.

The overall assessment confirms that no single Nature-Based Solution simultaneously maximizes technical performance, environmental sustainability, economic viability, and operational simplicity. Technologies achieving high pollutant removal efficiencies often require larger land areas or more complex operation, whereas low-cost and low-energy systems may exhibit lower hydraulic loading capacities or greater sensitivity to site-specific environmental conditions. Likewise, although many NBS provide additional ecosystem services and contribute to reducing greenhouse gas emissions, potential limitations—including nutrient leaching, contaminant accumulation, pathogen persistence, and long-term maintenance requirements—should also be considered during technology selection. Consequently, the choice of the most appropriate NBS should be based on a balanced evaluation of these technical, environmental, economic, operational, and social trade-offs within the specific conditions of each site.

8. Conclusions

This review provides a comprehensive and multidimensional assessment of NBS for decentralized wastewater treatment by integrating technical, economic, environmental, and social perspectives. The analysis demonstrates that NBS represent viable and sustainable alternatives to conventional wastewater treatment technologies, particularly in rural and peri-urban settings.

From a technical perspective, many NBS can achieve pollutant removal efficiencies comparable to those of conventional systems for specific contaminants. However, their performance remains highly variable and depends strongly on system design, operating conditions, and influent characteristics. Their principal limitations are generally associated with lower hydraulic loading rates and greater land requirements, which restrict their applicability in high-density or high-flow settings.

From economic and environmental perspectives, NBS offer clear advantages, including generally lower construction costs, reduced energy demand, and the provision of valuable ecosystem services. However, current economic assessments remain largely focused on capital costs, while other important life-cycle cost components, such as operation and maintenance, land requirements, monitoring, media replacement, sludge or biomass management, and end-of-life costs, are less consistently reported. Consequently, although NBS are generally considered economically attractive for decentralized applications, more comprehensive life-cycle economic assessments are needed to support robust comparisons among different technologies, particularly in resource-limited regions where simple operation and low operating costs are essential.

The review also highlights that the performance of NBS is inherently context-dependent and cannot be generalized across different environmental and socio-economic settings. Consequently, successful implementation requires careful system design, adaptation to local conditions, and, in many cases, the integration of complementary technologies within hybrid treatment configurations.

Social acceptance and effective governance emerged as equally important determinants of long-term project success. Community engagement, stakeholder participation, institutional support, and appropriate governance arrangements are essential to ensure public acceptance, reliable operation, and the long-term sustainability of NBS.

Among the technologies reviewed, vertical-flow constructed wetlands, horizontal-flow constructed wetlands, and hybrid configurations combining both systems consistently demonstrated a favourable balance between treatment performance, hydraulic loading capacity, energy demand, and construction costs. These technologies also exhibited high removal efficiencies for conventional pollutants and, in many cases, for heavy metals and contaminants of emerging concern. Microalgae-based systems also show considerable potential but require further research to better characterize their economic performance, hydraulic loading capacity, and operational requirements. Willow systems and slow-rate soil infiltration systems can achieve excellent treatment performance but are constrained by their high land requirements. Likewise, additional research is needed to better characterize the pollutant removal performance and representative hydraulic loading rates of waste stabilization ponds.

Overall, this review demonstrates that NBS are not a universal solution but rather a flexible portfolio of treatment technologies whose suitability depends on site-specific conditions and project objectives. Their successful implementation requires balancing technical performance, economic feasibility, environmental sustainability, and social and governance considerations within an integrated decision-making framework. Future research should focus on improving the predictability of system performance, optimizing hybrid treatment configurations, strengthening life cycle and economic assessments, and further

integrating social and governance aspects into the design and implementation of decentralized wastewater treatment systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18141775/s1>, Figure S1. Scheme of the different types of constructed wetlands, based on the work of Vymazal (2010) [11]. Figure S2. Reduction of different pollutants by different kinds of NBS. Table S1. Elimination efficiency of heavy metals by constructed wetlands, adapted from Zhang et al. (2024) [14]. Table S2. Elimination efficiency of heavy metals by different types of algae, adapted from Mahapatra et al. (2022) [53].

Author Contributions: Conceptualization, J.R.-C. and V.H.; Methodology, J.R.-C. and V.H.; Validation, V.H.; Formal analysis, J.R.-C. and V.H.; Investigation, V.H.; Resources, J.R.-C.; Data curation, V.H.; Writing—original draft preparation, V.H.; Writing—review and editing, J.R.-C. and V.H.; Visualization, J.R.-C.; Supervision, J.R.-C.; Project administration, J.R.-C.; Funding acquisition, J.R.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by RESET Project (PCI2025-167097-2) funded by MICIU/AEI /10.13039/501100011033 and co-funded by the European Union.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NBS	Nature-based Solutions
CW	Constructed Wetlands
IUCN	International Union for Conservation of Nature
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
TN	Total Nitrogen
NH ₄ ⁺ -N	ammonium nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
LCA	Life Cycle Assessment
TRL	Technology Readiness Level

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