Co-production as a mechanism for long-term Nature-based Solution viability: evidence from urban biofilters in an informal settlement of the Global South

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Abstract

Assessing the long-term viability of Nature-based Solutions (NbS) in vulnerable urban contexts remains a major methodological challenge. Existing frameworks emphasize technical performance, overlooking device survival and the socio-technical arrangements needed to sustain interventions over time. This study develops and empirically tests an integrated framework in which these three dimensions are interdependent, linked through feedback mechanisms. It was tested in a four-year longitudinal study (2019–2023) of a co-produced NbS intervention in the San Francisco stream (Claypole, Buenos Aires, Argentina), where 15 modular intermittent vertical-flow biofilters were implemented via a transdisciplinary partnership with a local social organization. Results showed that NbS viability emerged from interactions among the three dimensions rather than any single component in isolation. Biofilters consistently removed organic matter—chemical oxygen demand (COD) and dissolved organic carbon (DOC)—with performance varying seasonally and reaching its highest values in spring, whereas net dissolved nitrogen removal remained limited and highly variable across units. Device survival was determined by local hydraulic exposure (watershed side; $p = 0.009$) rather than cumulative rainfall, underscoring the role of site selection. The socio-technical arrangement sustained monitoring and maintenance throughout the COVID-19 restrictions, indicating that resilience depended as much on social organization as on hydraulic design. Together, these findings indicate that evaluating NbS in vulnerable urban contexts requires integrating technical performance, device survival, and socio-technical continuity. Co-production emerged not simply as a participatory strategy but as the mechanism coupling these dimensions, with implications for the design, evaluation, and scaling of NbS in urban peripheries of the Global South.

Keywords: vertical constructed wetlands; water pollution; transdisciplinary research; urban streams; urban social movements.

1. Introduction

Assessing the long-term success of Nature-based Solutions (NbS) in vulnerable urban contexts remains a fundamental methodological challenge. Most existing NbS assessment frameworks prioritize technical performance—such as pollutant removal, flow regulation, or infiltration capacity—as the primary indicator of intervention success (Rodak et al. 2019; IUCN 2020). However, in the urban peripheries of the Global South, where sanitation infrastructure is limited and implementation conditions differ substantially from laboratory settings or highly institutionalized cities, technical performance alone may be a necessary but insufficient condition for explaining whether an intervention ultimately succeeds (Frantzeskaki 2019; Wolff et al. 2022; Diep et al. 2022; Knapik et al. 2025).

Cities across the Global South face the combined pressures of rapid informal urbanization, watershed degradation, and persistent deficits in basic sanitation infrastructure (UNDESA 2018; Tzanakakis et al. 2020). Within this context, NbS have emerged as promising alternatives capable of simultaneously improving water quality while generating ecological and social co-benefits (Cohen-Shacham et al. 2016; Kabisch et al. 2016). Nevertheless, implementing NbS in informal settlements presents challenges that extend well beyond hydraulic or biogeochemical design. Long-term intervention success depends on adaptation to local implementation conditions, community engagement, distributed maintenance, and the capacity to withstand both physical disturbances and institutional disruptions (Le Coustumer et al. 2012; Pérez Rubi and Hack 2021; Prodanovic et al. 2022).

Recent literature highlights at least three limitations in current approaches to NbS evaluation. First, assessment frameworks frequently emphasize treatment performance while giving comparatively little attention to physical device survival and the continuity of the socio-technical arrangements required to sustain interventions over time (Frantzeskaki 2019; IUCN 2020). Second, evidence generated under controlled experimental conditions often fails to capture the variability and constraints of real-world implementation (Rodak et al. 2019). Third, maintaining operation and monitoring remains particularly difficult where institutional capacity is weak or fragmented, making long-term intervention continuity uncertain (Muwafu et al. 2024; Knapik et al. 2025). Consistent with this view, both the IUCN Global Standard for Nature-based Solutions (IUCN, 2020) and recent governance frameworks (van der Jagt et al., 2022) explicitly identify local ownership and distributed management capacity as criteria for long-term NbS success, yet these criteria are rarely operationalized or empirically tested alongside technical performance metrics within a single evaluation framework.

These limitations suggest that NbS viability should not be understood as the outcome of a single performance metric but rather as an emergent property arising from interactions among multiple dimensions operating simultaneously. In this study, NbS viability refers to the capacity of an intervention to sustain both its technical functionality and its socio-technical continuity over time under real implementation conditions. We argue that understanding this viability requires integrating three complementary dimensions: technical performance, physical device survival, and continuity of the socio-technical arrangement. While each dimension has been investigated individually, few studies have examined how they interact through feedback mechanisms that determine long-term intervention persistence.

Within this context, co-production has increasingly been proposed as an approach for designing and implementing NbS capable of integrating scientific knowledge with local experience (Raymond et al. 2017; Norström et al. 2020; DeLosRíos-White et al. 2020). Co-production is understood as an iterative process through which diverse actors jointly generate knowledge and coordinate action to address complex socio-ecological challenges (Wyborn et al. 2019; Chambers et al. 2021, 2022). The concept of *co-productive agility* proposed by Chambers et al. (2022) further emphasizes the capacity of heterogeneous actors to iteratively adapt, learn, and collectively generate solutions that could not have been anticipated from the outset. Despite these conceptual advances, empirical evidence demonstrating how co-production functions as the mechanism linking technical performance, device persistence, and long-term intervention continuity remains limited, particularly in longitudinal studies integrating these dimensions within a single analytical framework (Jacklin et al. 2022; Caitana and Moniz 2024).

Through a four-year longitudinal study of a co-produced NbS intervention implemented in a vulnerable metropolitan periphery of Buenos Aires, Argentina, this study develops and empirically evaluates an integrated framework for assessing long-term NbS viability. Specifically, it examines how co-production contributed to intervention continuity, how local hydraulic conditions influenced device survival, and how treatment performance evolved under real field conditions. By integrating these three analytical dimensions, the study identifies the feedback mechanisms through which long-term NbS viability emerges. In doing so, it moves beyond conventional performance-based evaluation and proposes an operational framework for assessing NbS under real implementation conditions in vulnerable urban contexts.

2. Materials and methods

2.1 Study area and socio-environmental context

The San Francisco stream is a low-gradient urban stream located in the San Francisco–Las Piedras sub-basin of the Sarandí–Santo Domingo River Basin, Buenos Aires Province, Argentina (34°49'S, 58°24'W). The study reach (approx. 1.25 km) traverses the Claypole neighborhood, an informally established and progressively consolidated urban area. In the absence of a sewage network—affecting 61% of the local population (INDEC, 2022)—domestic effluents are discharged into the stormwater drainage system and reach the receiving stream untreated (Gomez et al., 2025; Saraceno et al., 2021b), creating a chronic public health and environmental degradation scenario.

This configuration can be understood as a social-ecological trap, in which mutually reinforcing biophysical and social dynamics lock the system into an undesirable and persistent state (Boonstra & De Boer, 2013; Cinner, 2009; Graziano et al., 2021). Chronic pollution and the loss of ecological function drive a negative socio-environmental perception, whereby the stream is regarded not as an ecosystem but as an open sewer or drainage ditch. This perception legitimizes and entrenches conventional command-and-control management—channelization and aggressive hydraulic clearing that removes riparian vegetation—which in turn deepens the invisibilization of the ecosystem and reinforces dependence on external, infrastructure-heavy solutions, closing the feedback loop characteristic of a rigidity trap. Within this framing, the co-produced biofilter intervention is conceived as a deep leverage point: rather than treating symptoms, it seeks to shift the underlying management paradigm toward nature-based solutions while strengthening local actors, thereby destabilizing the trap and opening a pathway toward a more desirable social-ecological configuration.

Proyecto Hábitat Claypole (PHC) is a transdisciplinary space established in 2019 linking the Instituto Nacional del Agua (INA), the Facultad de Ciencias Exactas y Naturales of the Universidad de Buenos Aires (FCEN-UBA), and the Frente de Organizaciones en Lucha (FOL), a social organization with deep territorial roots in Claypole (Almirante Brown, Buenos Aires, Argentina). Its formation responded to the need to integrate technical capacities and local knowledge to address stream degradation under principles of socio-environmental justice and knowledge co-production (Gómez Lugo et al., 2025; Graziano et al., 2019; Saraceno et al., 2021a). The prior phase of this research line (Gomez et al., 2025) characterized the effluents entering the stream, identifying high loads of organic matter, nutrients, and fecal bacteria with marked seasonal variation. Those results, collectively discussed within PHC, constituted the technical starting point for biofilter design and are revisited in Section 4.1.

2.2 Co-production process

The study adopted an action-research co-productive approach organized in four successive stages (Figure 1): (i) background and diagnosis (2015–2019), consisting of the strengthening of actor linkages and the participatory identification of environmental problems; (ii) seasonal physicochemical characterization of the discharges (2019–2020); (iii) co-production and implementation of the biofilters (2019–2023); and (iv) discussion and evaluation of results and lessons learned. This scheme is consistent with co-production principles in sustainability science that prioritize practical orientation, actor plurality, and iterative learning among heterogeneous knowledge forms (Norström et al. 2020; Chambers et al. 2022).

The first two stages established the technical and relational groundwork for the intervention: PHC formalized the collaboration between INA, FCEN-UBA, and FOL and jointly identified stream degradation as a shared priority, before undertaking the seasonal sampling campaigns (2019–2020) that characterized the domestic discharges reaching the stream (Section 2).

The third stage, co-production and implementation (2019–2023), was the most extensive and iterative. Collective work sessions included design workshops (n = 3), a structural construction day (n = 1), and installation events (n = 6; December 16, 17, and 19, 2019, and December 13, 15, and 27, 2021), in which researchers, technicians, and FOL workers participated jointly. Knowledge production was embedded within the change process itself, enabling continuous recognition, repositioning, and navigation of tensions and opportunities that emerged throughout the intervention—including redesign of the initial prototype, adaptation during the COVID-19 pandemic, and progressive expansion of local capacities. Open workshops with model demonstrations, door-to-door outreach, and community awareness activities complemented the technical work. A biofilter team of five FOL members was trained in device assembly, installation, monitoring, and repair, and continuous follow-up was organized through an operational communication channel that functioned as a distributed monitoring system between the technical team and the territorial team.

Finally, the fourth stage consisted of the discussion and evaluation of results and lessons learned, carried out through three sessions with the community and local environmental organizations, in which the design, operation, and functioning principles of the biofilters were shared, together with the preliminary results obtained.

2.3 Biofilter design

Biofilters were designed as modular units based on intermittent vertical-flow constructed wetland principles (Stefanakis et al. 2014), conceived as low-cost, easily replicable, autonomous units capable of receiving domestic effluents without pretreatment and operating under the real conditions of the urban stormwater system. Two prototypes (0.6 m height × 0.6 m diameter) were developed iteratively. The first consisted of a structure of three stacked tires (Figure 2a–b), installed as an experimental pilot in September 2019; this design was subsequently replaced by a lighter and more discreet geotextile fabric container (400 μm, 150 L) (Figure 2c–d), adopted for both subsequent installation stages. The two designs differed mainly in their aeration system: the tire-based prototype used 53-mm PVC pipes, whereas the geotextile unit incorporated perforated 10-mm PVC pipes, providing passive and less visually conspicuous aeration while facilitating oxygen circulation within the substrate profile.

Both prototypes shared an identical five-layer granulometric gradient (15 cm per layer) arranged from the base upward: coarse gravel (20–40 mm) as the base layer, pumice stone as a porous biological support medium, expanded clay (LECA) as a reactive substrate for phosphorus retention, fine gravel (4–8 mm), and surface sand as the main filtering medium. Each unit was planted with *Typha latifolia* (Figure 2c–d), a native emergent macrophyte widely distributed in Buenos Aires Province, commonly used in treatment systems for its tolerance to domestic effluents and its capacity to transfer oxygen to the rhizosphere (Calheiros et al. 2009; Vymazal 2010).

Installation was organized in two stages: Stage 1 (December 2019–December 2021, n = 8) and Stage 2 (December 2021–April 2023, n = 7), both implemented with the geotextile-based design following the pilot-phase redesign (Section 4.2).

2.4 Performance monitoring

Seasonal sampling campaigns were conducted to characterize influent and effluent water quality. Samples were collected from biofilters operational at the time of each campaign, where operationality was defined by two concurrent conditions: physical integrity of the device and active wastewater discharge at the moment of sampling. This criterion explains why the number of sampled biofilters per campaign (n) may be lower than the total number of surviving units at that date. Campaigns were carried out in summer (January 7, 2022, n = 4; March 8, 2023, n = 4), autumn (May 9, 2022, n = 2; June 13, 2023, n = 1), and spring (October 11, 2022, n = 2).

For the survival analysis, the installation and failure date of each device were recorded, with failure defined as clogging, physical damage, or loss of functionality. Cumulative rainfall over the 15 days prior to failure was used as a proxy variable for rainfall effect on device durability, obtained from meteorological station 87576 SAEZ (-34.8167, -58.5333; Meteostat, 2025).

In each campaign, an integrated grab sample of approximately 5 L was collected at the inlet and outlet of each biofilter between 10:00 and 14:00 h, coinciding with peak domestic discharge periods. In-situ parameters measured were pH, electrical conductivity (EC), and dissolved oxygen (DO) (HACH HQ4300), and turbidity (HACH 2100P). Laboratory analyses included biological oxygen demand (BOD), chemical oxygen demand (COD), dissolved organic carbon (DOC), total suspended solids (TSS), ammonium, nitrates, total Kjeldahl nitrogen (TKN), soluble reactive phosphorus (SRP), and total phosphorus (TP), following standardized protocols (APHA 2018).

2.5 Statistical analysis

Treatment performance was evaluated using the Effluent Probability Method (EPM), which compares cumulative distributions of influent and effluent for each parameter without requiring temporally matched influent–effluent pairs, since sampling events were not always synchronized across all units (Pierobon et al. 2013); differences between distributions were tested with a one-tailed Mann-

Whitney U test (testing for influent > effluent; significance threshold: $p < 0.05$), without correction for multiple comparisons given the exploratory, parameter-specific nature of each test. Paired comparisons (Wilcoxon signed-rank test) were used only for pH and dissolved oxygen, for which matched inlet–outlet measurements were available for the same sampling event. Generalized linear mixed models (GLMMs) were employed to evaluate the relationship between removal efficiency and the explanatory factors of pollutant fraction (dissolved, mixed, particulate) and seasonality, incorporating biofilter identity as a random effect (glmmTMB, Brooks et al., 2017). The distribution of each response variable was examined to select the appropriate family and link function. In cases where normality or homoscedasticity assumptions were violated, alternative distributions such as Gamma (log link) or Tweedie, suitable for continuous positive data with non-constant variance, were applied. Assumptions were evaluated using diagnostic plots, statistical tests (Shapiro-Wilk), and scaled residuals (DHARMa, Hartig, 2016). Significant differences in main effects and interactions were assessed through ANOVA (Type II), while multiple comparisons between factor levels were performed using post hoc Tukey HSD tests (emmeans, Lenth & Piaskowski, 2017). Changes in pH and DO between inlet and outlet were evaluated using the Wilcoxon signed-rank test for paired samples (significance threshold: $p < 0.05$).

Device durability was evaluated through survival analysis. The failure event was defined as the recorded date of clogging, physical damage, or loss of functionality; devices that remained operational at the end of the study period were treated as censored observations. Kaplan–Meier curves were used to visualize durability between installation stages, and differences between stages were further assessed through a Cox proportional hazards model. A second Cox model quantified the influence of watershed side and cumulative precipitation on failure risk. Compliance with the proportional hazards assumption was verified through analysis of Schoenfeld residuals. All survival analyses were performed using the survival package (Therneau 2024) in R v.4.4. The multivariate removal pattern was characterized by Principal Component Analysis (PCA) on the standardized removal efficiency matrix (vegan, Oksanen et al., 2025). All analyses were conducted in R v.4.4 (R Core Team, 2025).

3. Results

3.1 Co-production and local capacity building

Between 2019 and 2023, PHC coordinated over fifteen collective work sessions, including construction workshops, results discussion meetings (Figure 3a), installation events (Figure 3c–g), and community awareness activities (Figure 3b). The biofilter team—comprising five FOL members—progressively assumed responsibilities spanning device assembly, installation, sampling, in-situ physicochemical determination, and systematic incident reporting. This technical appropriation required multiple practical training sessions, including setup of a mobile laboratory in the community space for SRP and nitrate determination (Figure 3f), and was traversed by COVID-19 pandemic interruptions.

The operational communication channel (messaging platform, WhatsApp) enabled biweekly documentation of device status throughout 2020 and 2021, when technical team presence was not feasible. Records included hydrological conditions, vegetation status, waste presence, and structural alterations. This distributed monitoring proved both an effective monitoring mechanism and a space for building trust between the academic team and the community. The joint meetings to discuss the results enabled sharing of preliminary findings and adjustment of monitoring design to local dynamics and timelines.

3.2 Biofilter development and implementation

Biofilter design evolved through an iterative process in three phases:

Pilot phase (September 2019): an experimental prototype based on three stacked tires was installed (Figure 2a–b). The first three campaigns yielded high removal rates (COD: 96%; TKN: 94%; TP: 91%; DOC: 54%), but the device was vandalized within three weeks due to the theft of the passive aerators, prompting a redesign toward a more discreet, lightweight, and easy-to-construct unit.

Stage 1 (December 2019–December 2021): Eight biofilters with geotextile fabric pots (400 μm, 150 L) were installed (Figure 4b). The COVID-19 pandemic prevented systematic monitoring; follow-up was sustained through biweekly team rounds and WhatsApp-based reporting.

Stage 2 (December 2021–April 2023): Seven additional biofilters were installed, built entirely by the team (Figure 4b).

3.3 Device survival

Kaplan–Meier curves showed a trend toward higher survival in Stage 2 (median: 528 days) compared to Stage 1 (median: 110 days) (Figure 5). However, the Cox model adjusted by stage yielded a hazard ratio (HR) of 0.90 (95% CI: 0.30–2.74; p = 0.86), indicating that the difference between stages was not statistically significant. When covariates were incorporated, the watershed side emerged as a significant survival determinant (p = 0.009): biofilters on a specific side of the catchment exhibited a significantly higher failure risk, regardless of the installation stage. In contrast, cumulative rainfall over the 15 days prior to failure was not significant (p = 0.86), indicating that accumulated hydraulic load was not the primary durability driver, contrary to initial expectations.

3.4 Influent characterization

The collected urban effluents exhibited variable pollutant loads across seasons, with COD, TSS, and TKN concentrations particularly elevated in summer and spring (Table 1). In terms of composition, the discharges showed a pattern consistent with domestic greywater (kitchen, bathroom, and laundry sources) (Gomez et al. 2025).

The spring peak in particulate load, coinciding with elevated organic matter and phosphorus concentrations (Table 1), points to an intensified mobilization of solids and associated pollutants during that period. Taken together, these baseline concentrations characterize an untreated domestic effluent with high and temporally heterogeneous organic and solid loads, and a nitrogen pool dominated by reduced species. This influent profile establishes the loading conditions against which treatment performance and its seasonal modulation are evaluated in the following sections (Section 4.5) and helps explain both the robust retention of organic matter and particulates and the limited net removal of dissolved nitrogen reported below.

3.5 Treatment performance

The EPM revealed statistically significant differences between influent and effluent for COD and DOC ($p < 0.05$), with consistent cumulative curve separation indicating robust organic matter reduction (Figure 6). For BOD, separation was clear at low to intermediate concentrations, but efficiency decreased at high concentrations, consistent with oxygen limitations, reduced effective residence time, and/or preferential flow paths associated with clogging (Le Coustumer et al. 2009).

For nutrients, influent and effluent cumulative distributions were nearly coincident for ammonium, TKN, and dissolved inorganic nitrogen. For nitrates, a moderate increase was observed at the lower quantiles, without a global shift indicating sustained net transformation. This pattern is more consistent with episodic partial nitrification followed by leaching, or substrate release, than with stable system-scale nitrification (Søberg et al. 2021). Paired pH and DO analysis showed no significant differences between inlet and outlet in any season (Wilcoxon, $p > 0.10$).

3.6 Seasonal modulation and inter-unit heterogeneity

Overall removal efficiency was significantly higher in spring than in autumn ($p < 0.05$), with summer in an intermediate position without significant differences relative to other seasons. This pattern was especially pronounced for organic matter: COD (spring: 47 ± 18% [mean ± SD]; autumn: 13 ± 25%), BOD, and DOC. For SRP, significant differences were detected between spring and autumn, with higher spring removal (21 ± 10%).

Pollutant fraction also influenced efficiency: the mixed fraction showed significantly higher removal than the dissolved fraction ($p < 0.05$), consistent with the dominance of physical retention and adsorption mechanisms (Rodak et al. 2019). PCA explained 62% of the variance in the removal matrix and showed clear seasonal differentiation: spring and summer samples clustered at positive axis-

1 values, associated with COD, BOD, DOC, and TKN; autumn samples shifted toward negative values (Figure 7). Unit-level analysis revealed marked heterogeneity among nominally equivalent biofilters: B9 and B11 showed relatively stable removal, while B14 and B15 exhibited pronounced fluctuations including negative nitrate removal in some campaigns (Figure 7).

4. Discussion

Our results support the proposed framework: NbS viability in vulnerable territories was not explained by any single dimension, but by the quality of their interactions. Organic matter removal was consistent and seasonally modulated; device survival was determined by spatial exposure rather than rainfall load; and the continuity of the socio-technical arrangement—through the maintenance team and the distributed communication channel—was the key factor sustaining both monitoring and device operation during the COVID-19 pandemic. Together, these findings demonstrate that evaluating NbS success in vulnerable contexts requires simultaneously attending to technical performance, physical device survival, and socio-technical arrangement, and that co-production emerged as the functional mechanism articulating all three.

4.1 Co-production as a functional enabler

Our study demonstrates that co-production did not operate as an accessory component, but as a functional enabler of viability—in the sense sustainability science assigns to it: actor plurality, practical orientation, and iterative learning among heterogeneous knowledge forms (Norström et al. 2020; Chambers et al. 2021, 2022). We observed that technical-scientific knowledge integrated with local knowledge about materials, tools, and territorial dynamics, generating a shared language for design decisions, protocol adjustment, and operational continuity: what Chambers et al. (2022) characterize as co-productive agility. Without the maintenance team and distributed monitoring network, survival tracking during the pandemic would have been impossible; without pre-design awareness processes, Stage 2 expansion would have lacked territorial legitimacy.

Our findings showed that capacity building was not merely instrumental—transferring installation or sampling skills—but that it constructed local autonomous management capacity: an outcome the IUCN Global Standard (IUCN 2020) establishes as an NbS quality criterion, and that urban governance frameworks identify as indispensable for long-term sustainability (Frantzeskaki 2019; Yuan et al. 2025; Galdámez et al. 2025).

Monitoring continuity during COVID-19 illustrates the system's socio-technical resilience. When mobility restrictions interrupted conventional monitoring, the territorial network sustained observation, recording, and incident communication. From the perspective of Chambers et al. (2022), this capacity expresses *co-productive agility* in action: PHC and the team redirected their agendas, navigated health restriction tensions, and sustained the co-production process through the distributed communication channel—without losing socio-technical coherence. This result aligns with Frantzeskaki's (2019) argument that low-operational-burden monitoring schemes with committed actors reduce coordination costs, maintain event traceability, and facilitate systematic learning capture, increasing system resilience.

In the sustainable drainage literature, the lack of distributed operation and maintenance capacities is consistently identified as the primary cause of performance loss in locally scaled NbS (Muwafu et al. 2024; Yevenes et al. 2025; Knapik et al. 2025). Co-produced participatory assessment not only ensures monitoring continuity beyond the project funding cycle, but strengthens local appropriation and autonomous NbS management capacity (van der Jagt et al. 2022).

4.2 Iterative prototype development: *in-situ* learning and territorial viability

The evolution from the tire prototype to the geotextile pots built by the team illustrates a principle frequently overlooked in NbS evaluation: territorial viability is as important as treatment efficiency. The pilot phase demonstrated that a technically functional prototype can be territorially unviable if it generates visual rejection, attracts vandalism, or is installed without necessary community legitimacy. This replicates findings from informal setting studies indicating that social adoption of green infrastructure requires authentic co-design, not merely one-directional outreach (Raymond et al. 2017; Pérez Rubi and Hack 2021; Chapa et al. 2023).

4.3 Survival and spatial exposure: watershed side as dominant driver

The finding that watershed side was a significant survival predictor while cumulative rainfall was not represents a counterintuitive result with relevant practical implications for NbS design in urban environments. In urban systems, the first flush typically concentrates the highest solid and pollutant loads (Lee et al. 2002), and can generate differential hydraulic pulses depending on local catchment topography. A plausible hypothesis is that the higher-failure-risk side experiences more severe hydraulic conditions—higher entry velocity, greater solid transport, higher clogging potential—independently of total accumulated rainfall. This suggests that site assessment for biofilter installation should incorporate local hydraulic exposure analysis beyond regional rainfall analysis.

Inter-unit heterogeneity among nominally equivalent biofilters—particularly evident in B14 and B15—reinforces this argument: differences in flow distribution, local clogging, and maintenance accessibility may be more determinant than original design characteristics (Payne et al. 2014). These spatial conditioning factors are frequently underestimated in NbS assessments that prioritize aggregate performance metrics over spatial variability analysis (Prodanovic et al. 2022).

4.4 Treatment performance: scope, limits, and mechanisms

The consistent removal of organic matter (COD, DOC) confirms the functional capacity of the biofilters under real field conditions, in line with the biofiltration literature where organic matter indicators respond more robustly than nutrients, particularly when hydraulic residence time is variable (Bratieres et al. 2008; Wu et al. 2017; Rodak et al. 2019). The seasonal dependence observed—higher efficiencies in spring and lower in autumn—is congruent with increased microbial activity and biofilm development at higher temperatures (Ge et al. 2016; Adyel et al. 2016; Beral et al. 2023), and with the role of *Typha latifolia* in nutrient assimilation and rhizosphere oxygenation during active growth periods (Vymazal 2010).

Performance limits were most apparent in dissolved nitrogen removal. The absence of stable nitrification—evidenced by the lack of significant pH and DO changes and by the episodic nitrate increases—is consistent with systems where redox conditions were insufficient to sustain complete nitrification or denitrification, rather than residence time alone: the oxygenated conditions observed in our biofilters suggest that the limiting factor was the absence of sustained anoxic zones required for denitrification (Søberg et al. 2021; Biswal et al. 2022). In contexts where nitrogen loading is a management priority, intermittent vertical-flow biofilters operating under the residence times observed here may be insufficient as a standalone solution, and would require complementary treatment strategies or design modifications to increase hydraulic contact time and redox zone diversity (Payne et al. 2014; Fowdar et al. 2017).

The higher removal efficiency of the mixed fraction relative to the dissolved fraction reinforces the argument that the dominant mechanisms in these systems are physical—retention, filtration, and adsorption—rather than biogeochemical. Modular-scale biofilters are effective for reducing organic matter and solid loads in untreated domestic effluents, but should not be benchmarked against secondary treatment systems designed for complete nutrient removal. Of note, similar low-impact systems have been reported to increase rather than reduce SRP concentrations under low influent loads or dry climate conditions (Zhou et al. 2024), further underscoring the need to contextualize performance expectations according to the specific effluent matrix.

4.5 Synthesis: toward an integrated NbS assessment framework for vulnerable contexts

Integrating the three analytical dimensions reveals an emergent framework in which technical performance, device survival, and continuity of the socio-technical arrangement function as mutually reinforcing components rather than independent dimensions (Figure 8). Rather than representing separate evaluation criteria, these dimensions are connected through feedback loops that collectively determine long-term NbS viability. The principal empirical contribution of this longitudinal co-production process lies in identifying the direction and function of these feedbacks.

The first feedback loop links device survival to technical performance. Because treatment performance can only be quantified while a unit remains operational, the generation of technical evidence depends directly on device survival. Kaplan–Meier analysis demonstrated that survival was determined by local hydraulic exposure—specifically, the watershed side (p = 0.009)—rather than by cumulative rainfall. Consequently, units that failed early no longer contributed to the performance record, biasing the available dataset toward better-protected locations. Device survival is therefore a necessary, although not sufficient, condition for generating reliable technical knowledge. Consequently, site selection that minimizes hydraulic exposure becomes a prerequisite not only for successful implementation but also for robust performance evaluation.

The second feedback loop links the continuity of the socio-technical arrangement to device survival. This relationship emerged as the principal determinant of intervention continuity. The distributed maintenance network sustained by the PHC and the FOL biofilter team detected clogging and structural failures, coordinated repairs, and maintained the monitoring program throughout the COVID-19 restrictions—a period during which a conventionally managed, externally maintained intervention would likely have been discontinued. Without this socio-technical arrangement, higher device loss and a substantially smaller evidence base would have been expected. These findings therefore suggest that resilience during an external perturbation of exceptional magnitude depended primarily on the continuity of the socio-technical arrangement rather than on hydraulic design alone.

The third feedback loop closes the cycle by linking technical evidence to the legitimacy of the socio-technical arrangement. The collectively generated evidence—namely the consistent, seasonally modulated reduction of organic matter under real field conditions—appeared to strengthen confidence in the co-produced process by providing tangible evidence of its effectiveness.

Community participants observed that their collective efforts generated verifiable technical results, reinforcing local ownership and their willingness to sustain monitoring and maintenance activities. In turn, this strengthened the continuity and long-term stability of the socio-technical arrangement, completing a self-reinforcing cycle.

Taken together, these three feedback loops indicate that no single dimension can be optimized in isolation. Instead, long-term NbS viability emerges from the interactions among technical performance, device survival, and socio-technical continuity, with co-production acting as the mechanism that couples these dimensions.

These interdependencies suggest that long-term NbS success cannot be adequately assessed by evaluating each dimension separately. Instead, the proposed framework complements two widely used references in NbS assessment. The IUCN Global Standard (IUCN 2020) provides quality criteria primarily focused on ecosystem performance and inclusive governance but does not explicitly incorporate physical device survival or hydraulic exposure as determinants of intervention durability. Similarly, the participatory assessment framework proposed by van der Jagt et al. (2022) advances the integration of community actors into urban NbS monitoring but places comparatively less emphasis on inter-unit variability and localized physical conditions.

In contrast, the framework proposed here assigns equal analytical importance to all three dimensions and demonstrates that the continuity of the socio-technical arrangement is as critical to long-term intervention success as hydraulic-biogeochemical design optimization. Furthermore, our findings indicate that co-produced monitoring should not be viewed merely as a low-cost alternative to conventional monitoring but as a methodologically robust evaluation approach in its own right—distributed, operationally efficient, and well adapted to vulnerable urban contexts (van der Jagt et al. 2022; Muwafu et al. 2024; Knapik et al. 2025).

Regarding transferability, our findings are applicable to contexts sharing similar socio-environmental characteristics, although implementation necessarily requires adaptation to local conditions. Three enabling conditions appear essential: (i) the presence of a locally rooted social organization capable of sustaining long-term engagement; (ii) a transdisciplinary coordination space that facilitates integration between scientific and local knowledge; and (iii) a modular technological design that can be implemented, maintained, and monitored by non-specialized actors. Recent NbS co-production experiences in the Global South—including those reported in Brazil (Lemes de Oliveira et al. 2025) and comparative analyses of living laboratories in Latin America and Europe (Galdámez et al. 2025)—suggest that this framework can be successfully adapted across comparable urban contexts when these enabling conditions are met.

5. Conclusions

This study develops and empirically evaluates an integrated framework for assessing the long-term viability of Nature-based Solutions in vulnerable urban environments. The framework is built around three interdependent dimensions: technical performance, device survival, and continuity of the socio-technical arrangement. Four years of longitudinal evidence from the San Francisco stream demonstrate that long-term NbS viability does not arise from optimizing any single dimension but from the quality of the feedbacks connecting them. Within this framework, co-production is not an auxiliary implementation strategy but the functional mechanism through which these interactions are sustained.

The principal methodological contribution of this study is to show that evaluating NbS in socially and environmentally vulnerable contexts requires integrating all three dimensions within a single assessment framework. Evaluation approaches focused exclusively on treatment efficiency overlook the processes that determine long-term intervention persistence. In our case, local hydraulic exposure—not cumulative rainfall—explained device survival, whereas the continuity of the socio-technical arrangement emerged as the principal factor sustaining system resilience during an external perturbation of exceptional magnitude.

These findings have direct implications for NbS governance and scaling in the Global South. Co-produced monitoring should not be understood as a low-cost substitute for technical monitoring but as a scientifically valid evaluation strategy that simultaneously generates technical evidence, strengthens local ownership, and supports long-term intervention continuity. Consequently, the evidence generated through implementation is not independent of the socio-technical process that produces it; rather, it becomes one of the mechanisms through which long-term viability is reinforced.

Although the framework was developed under the specific environmental and institutional conditions of the San Francisco stream, its underlying logic is potentially transferable to comparable urban peripheries, provided that implementation is adapted to local hydrological, social, and governance conditions.

Future research should evaluate this framework across larger numbers of sites and broader environmental settings, explore complementary design strategies to improve nitrogen removal, and develop standardized indicators for systematically assessing the socio-technical dimension across comparable NbS interventions.

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Author contributions

Conceptualization: Bárbara M. Gomez, Rodrigo Sinistro, Martín Graziano. Methodology: Bárbara M. Gomez, Camila Saveika, Martín Graziano. Formal analysis and investigation: Bárbara M. Gomez, Camila Saveika, Martín Graziano. Writing – original draft preparation: Bárbara M. Gomez, Martín Graziano. Writing – review and editing: Bárbara M. Gomez, Rodrigo Sinistro, Martín Graziano. Funding acquisition: Bárbara M. Gomez, Rodrigo Sinistro, Martín Graziano. Supervision: Martín Graziano. Project administration: Martín Graziano

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Declarations

Conflict of interest: The authors declare no conflict of interest.

Data availability: The data that supports the findings of this study are available upon reasonable request.

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Tables

Table 1. Seasonal characterization of biofilter influents. Median (min–max); mg L^{-1}. nd: no data collected.

Parameter	Summer	Autumn	Spring
COD	464.5 (115-820)	203.5 (33-447)	302.5 (76-1628)
BOD	76 (26-145)	35 (12-66)	27 (17-111)
DOC	38.6 (15.2-158.3)	33.5 (24.0-68.3)	41.2 (14.0-260.0)
TKN	15.2 (2.8-23.0)	7.3 (0.6-13.4)	16.7 (10.6-64.0)
Ammonium	8.5 (0.2-15.8)	2.6 (0.1-9.6)	10 (3.7-17.9)
Nitrates	1.4 (1.2-7.4)	nd	1.7 (0.8-4.5)
SRP	0.3 (0.1-1.8)	0.1 (0.1-1)	1.1 (0.3-1.3)
TP	1.6 (1.2-3.1)	0.9 (0.1-1.2)	2.1 (1.2-4.6)
TSS	115.5 (28-483)	116.5 (16-207)	427.5 (209-1354)

Figures

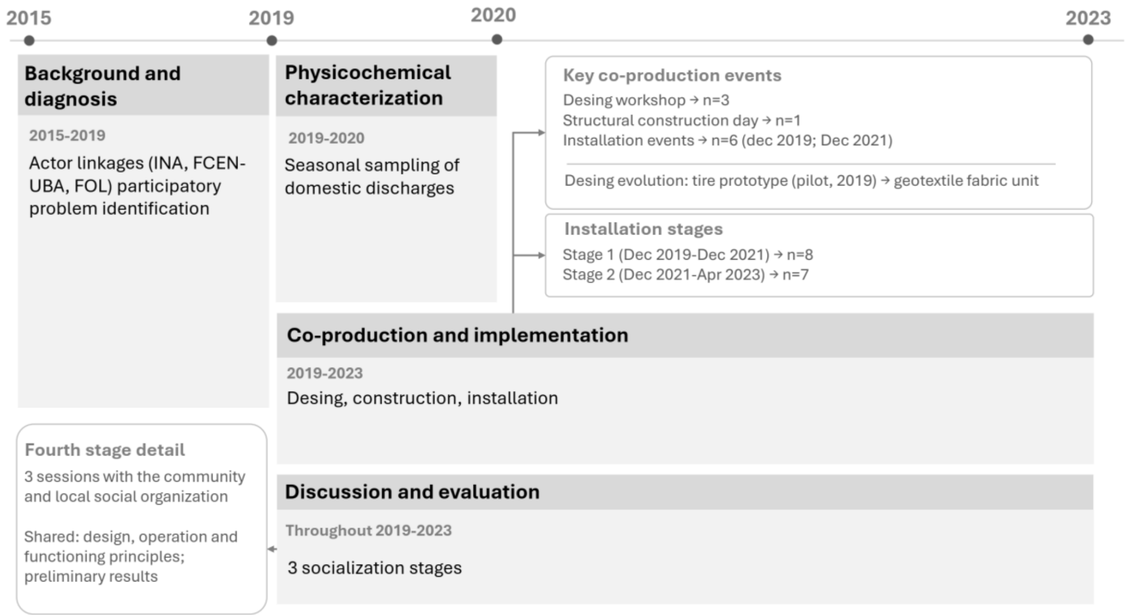

Figure 1. Schematic overview of the co-production process (2015–2023). The timeline distinguishes four phases: background and diagnosis, physicochemical characterization, co-production and implementation, and discussion and evaluation of results. The co-production and implementation phase (2019–2023) comprised design workshops (n = 3), a structural construction day (n = 1), and installation events (n = 6; December 2019 and December 2021), during which the design evolved from an initial tire-based prototype (pilot phase, September 2019) to 150 L geotextile fabric units. Biofilter installation proceeded in two stages: Stage 1 (December 2019–December 2021, n = 8) and Stage 2 (December 2021–April 2023, n = 7), the latter built entirely by the local team. Throughout the process, three sessions were held to discuss results and share lessons learned with the community and local environmental organizations.

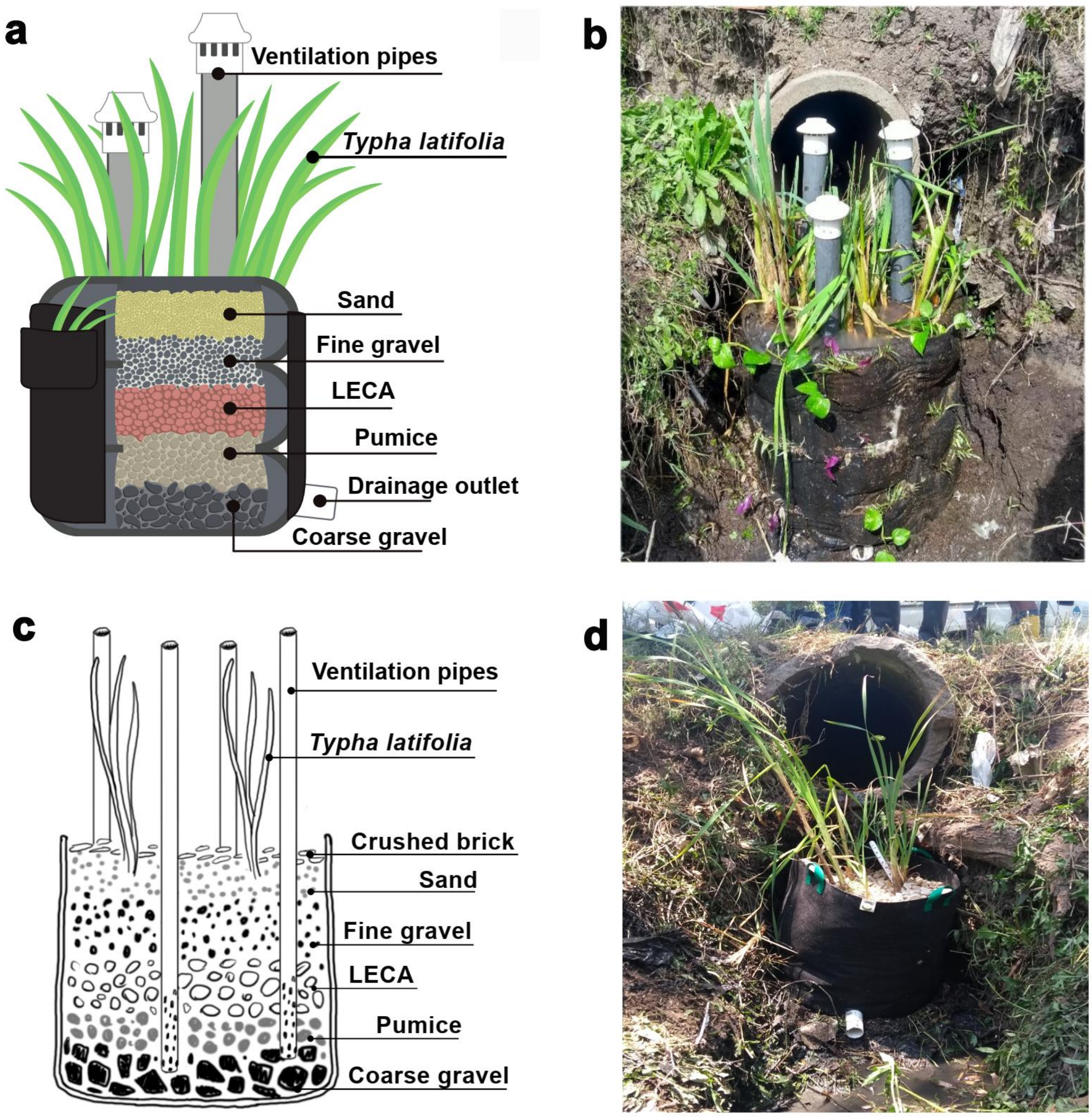

Figure 2. Biofilter design. (a) Schematic of the first design: three stacked tires with layers of sand, fine gravel, LECA, pumice, and coarse gravel; 53-mm PVC aerators. (b) Prototype installed September 2019. (c) Schematic of the second design: 400-μm geotextile fabric pot (150 L); 10-mm PVC aerators. (d) Biofilter installed December 2019.

Figure 3. Co-production process. (a) Results discussion and planning workshop (November 8, 2021). (b) Infographics and model used in community outreach activities. (c) Site preparation and biofilter installation at stormwater drain outlets. (d–e) Installed biofilters in the field. (f) Mobile laboratory set up at the social organization's premises for nitrate and SRP determination. (g) PHC team that participated in installation events and sustained biofilter maintenance

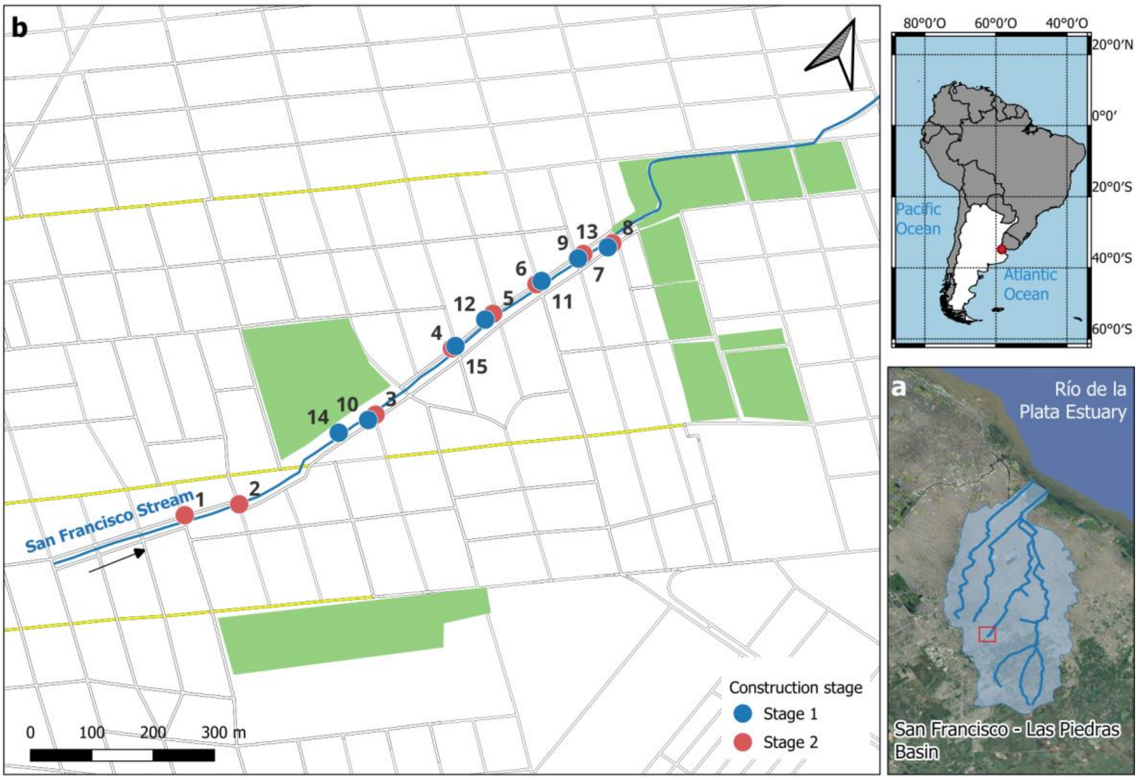

Figure 4. Study area and spatial distribution of the biofilters. a) Location of the study reach (red square) within the San Francisco–Las Piedras stream basin, discharging into the Río de la Plata Estuary. b) Detailed view of the ~1.25 km study reach along the San Francisco stream (blue line) in Claypole, Almirante Brown district. Dots indicate the spatial layout of the 15 pilot biofilters with their respective identification codes (1 to 15). Colors distinguish the two implementation phases: Stage 1 (blue dots; December 2019–December 2021) and Stage 2 (red dots; December 2021–April 2023). The black arrow indicates the direction of streamflow.

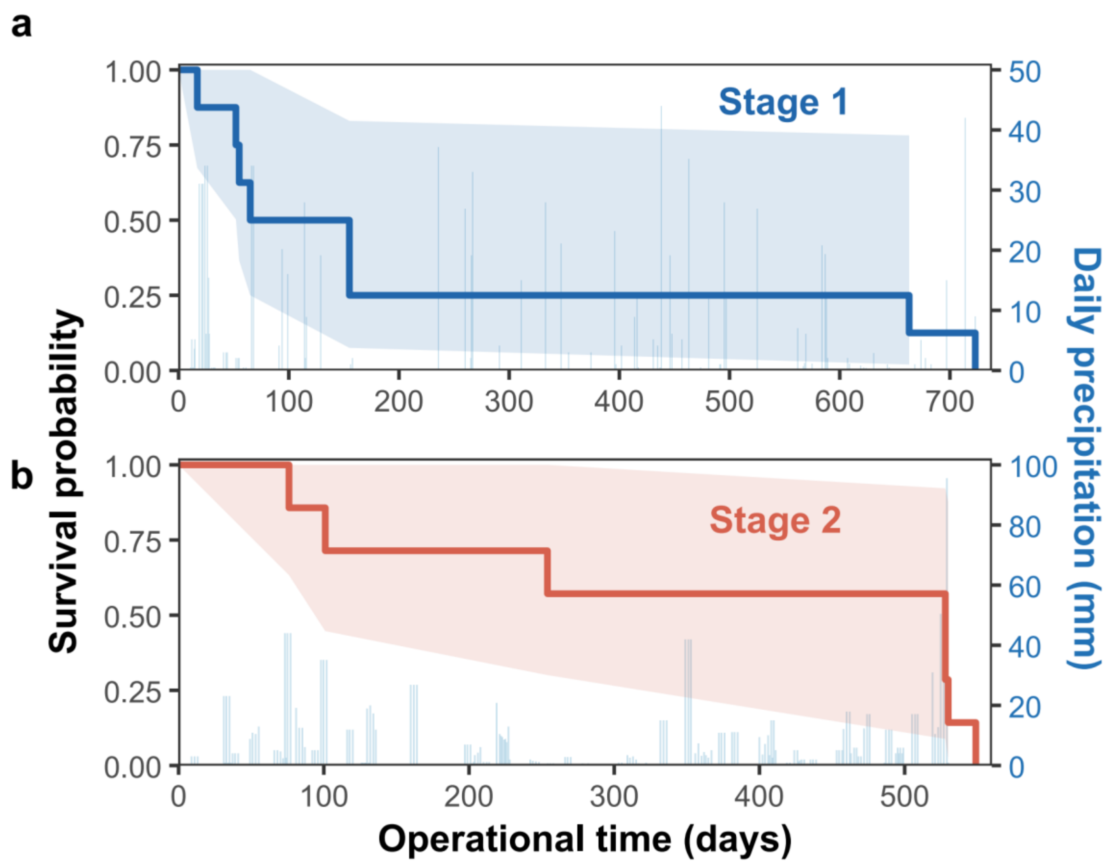

Figure 5. Kaplan–Meier survival curves and cumulative precipitation. (a) Stage 1 biofilters (December 2019–December 2021). (b) Stage 2 biofilters (December 2021–April 2023).

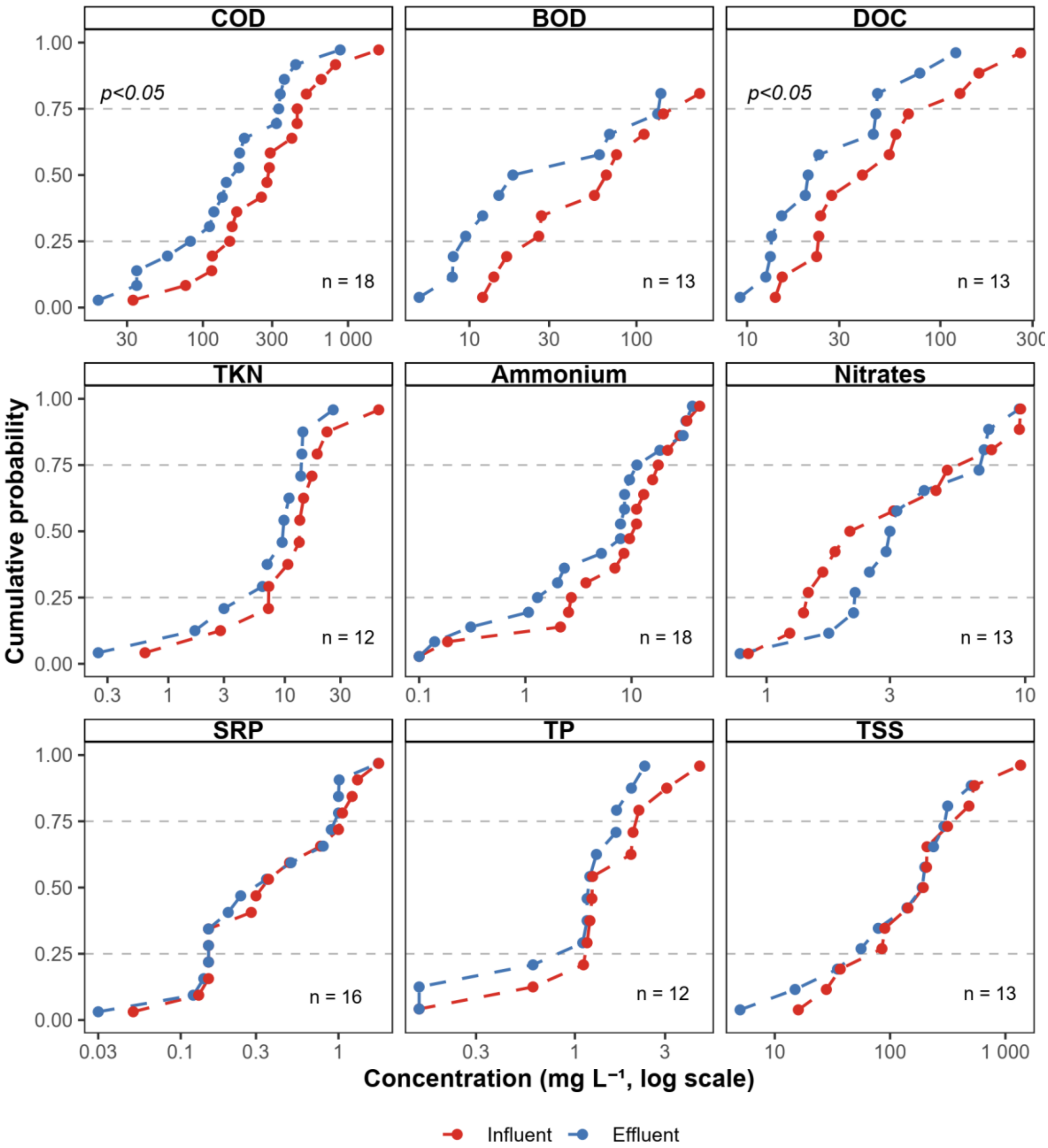

Figure 6. Treatment performance. Cumulative probability curves (EPM) for influent and effluent for each parameter. The x-axis is on a logarithmic scale.

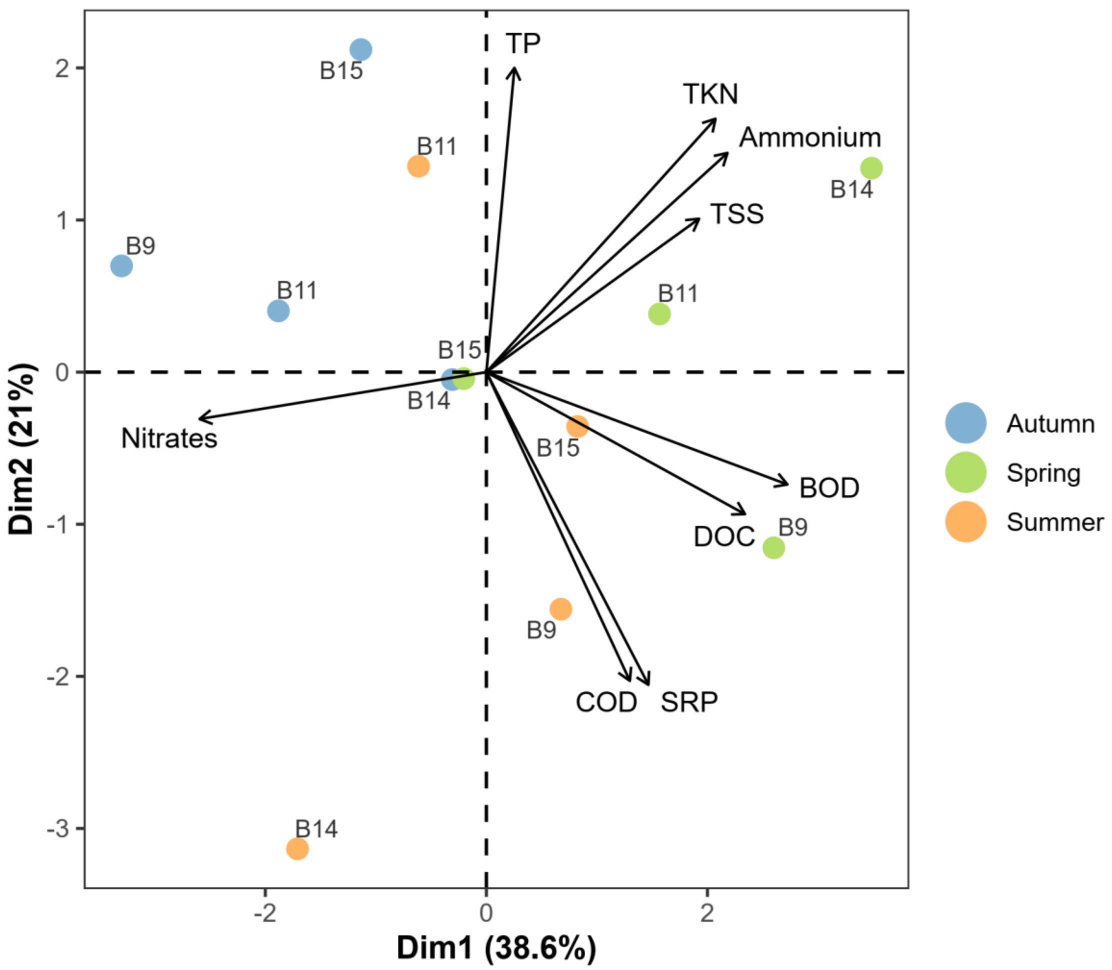

Figure 7. Principal Component Analysis (PCA) of unit-level removal efficiency. Points represent individual biofilters colored by season; arrows indicate the correlation of each parameter with the principal axes

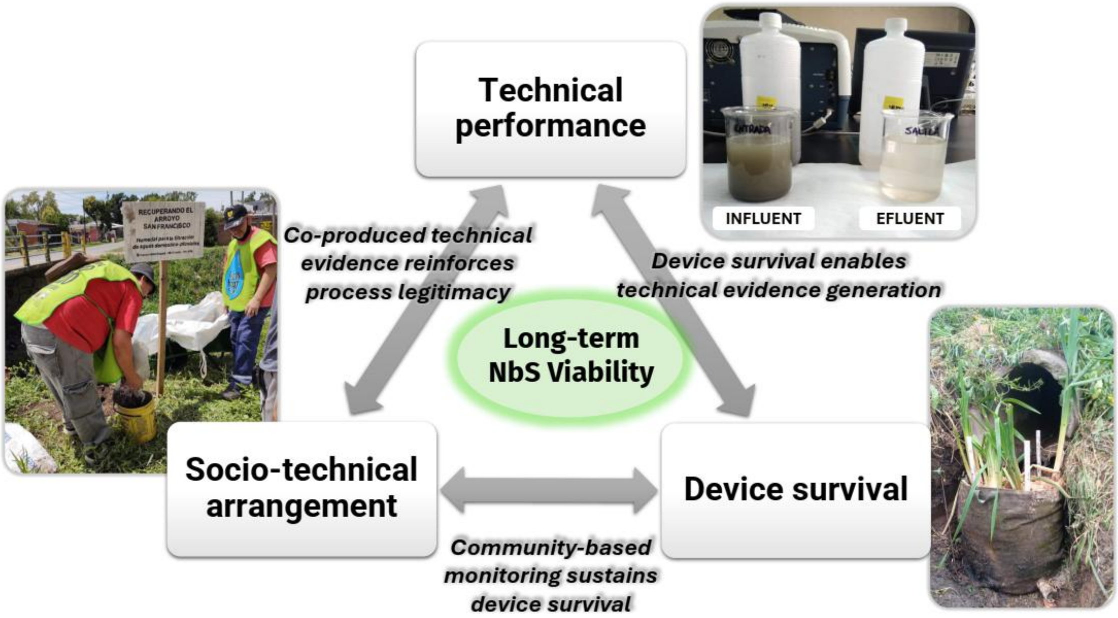

Figure 8. Integrated assessment framework for long-term NbS viability in vulnerable urban environments. The framework integrates three interdependent dimensions: technical performance (pollutant removal under field conditions), device survival (determined by local hydraulic exposure), and continuity of the socio-technical arrangement (community engagement, distributed maintenance, and governance). The arrows represent the feedback mechanisms linking these dimensions: device survival enables the generation of technical evidence; co-produced technical evidence strengthens process legitimacy and local ownership; and community-based monitoring detects failures, sustains operation, and promotes long-term continuity. Together, these feedbacks illustrate how long-term NbS viability emerges from the interaction between technical and socio-technical processes rather than from any single dimension in isolation.