

# Constructed wetlands as nature-based solutions for wastewater treatment: A scoping review of iucn global standard reporting and complementary advanced oxidation polishing

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## ABSTRACT

Wastewater treatment remains a critical challenge for water security, ecological integrity, and public health. Constructed wetlands (CWs) are widely advanced as nature-based solutions (NbS) because they use ecosystem processes for water purification and can deliver ecological co-benefits. This scoping review mapped 36 peer-reviewed studies (2010–2025; 63 extracted records) evaluating CWs used alone or within CW-based treatment trains incorporating advanced oxidation processes (AOPs) as pre-treatment or post-polishing. Outcomes covered conventional pollutants, selected micropollutants, and microbial indicators; PFAS and antibiotic-resistance indicators were assessed where reported. Vertical subsurface-flow and hybrid CWs generally reported high removal of COD, TN, and TP and meaningful reductions of indicator bacteria, supporting secondary treatment objectives. Micropollutant evidence was heterogeneous and compound-specific; carbamazepine showed limited attenuation. PFAS reporting in the mapped corpus was sparse and, where present, indicated variable, compound-dependent attenuation rather than demonstrable absence. No included studies provided extractable antibiotic-resistance gene outcomes. AOP units (e.g., ozonation, UV/H<sub>2</sub>O<sub>2</sub>, photo-Fenton) were associated with positive within-study deltas in some cases but were matrix-dependent and carry energy/chemical demands and potential transformation products requiring monitoring. IUCN Global Standard assessment was applied to the CW intervention only, revealing stronger reporting for problem framing and design intent and persistent gaps in equity, inclusiveness, and policy coherence.

## Introduction

The management of wastewater remains one of the most pressing environmental and public health challenges of the twenty-first century. Nearly 80 % of global wastewater is still discharged into rivers, lakes, and coastal zones without adequate treatment, exposing close to two billion people to unsafe water for drinking and irrigation [1]. Such untreated discharges undermine progress towards Sustainable Development Goal 6 (Clean Water and Sanitation) and compromise ecological integrity by introducing nutrient surpluses, pathogens, trace organics, and emerging contaminants into fragile ecosystems [2]. These pressures are compounded by rapid urbanization, growing water demand, and climate change, which together elevate wastewater recovery and reuse to a strategic priority for water security, agricultural resilience, and climate adaptation. In this context, Nature-based Solutions (NbS) have

gained increasing prominence as integrated approaches that link ecological sustainability with human well-being. The formal IUCN definition frames NbS as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” [3]. This definition establishes a dual expectation (societal effectiveness and biodiversity integrity) that distinguishes NbS from conventional technological substitutions [4]. The IUCN Global Standard for NbS, comprising eight criteria and twenty-eight indicators, operationalizes this integrity requirement by specifying how NbS interventions should be designed, governed, monitored, and scaled, including explicit attention to participation, equity, biodiversity outcomes, trade-offs, adaptive management, and policy coherence [3]. The Standard is not a generic sustainability label: its application requires that the intervention be clearly bounded and

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supported by documentary evidence for the relevant indicators [3]. Recent applications of the Standard underline this evidentiary logic, showing that appraisal depends on explicit records of stakeholder engagement, biodiversity baselines and monitoring, and adaptive management commitments [5,6]. This emphasis on verifiable criteria responds to a broader scholarly concern that rapid mainstreaming can dilute the concept through mislabeling or “greenwashing,” undermining comparability and credibility [7–10]. Within European policy, the Green Deal similarly frames NbS as scalable infrastructures that embed ecological processes into cities, landscapes, and industrial systems while delivering co-benefits beyond single-purpose performance [11]. In parallel, policy and scholarly work on green–grey or hybrid infrastructure emphasizes that NbS can be integrated with engineered measures, but that rigorous appraisal requires analytical separation of ecosystem-based contributions from engineered performance outputs [12–14]. Among NbS approaches relevant to water quality, constructed wetlands (CWs) stand out as engineered analogues of natural wetlands designed to harness sedimentation, filtration, adsorption, precipitation, and microbial degradation for wastewater treatment. When appropriately designed and operated, CWs achieve substantial removal of conventional pollutants; reductions in biochemical oxygen demand and suspended solids often exceed 70–90 %, and vertical-flow systems can achieve strong attenuation of microbial indicators through filtration and die-off processes. The ecological co-benefits associated with wetland interventions should, however, be articulated with conceptual precision. Foundational ecosystem services frameworks define ecosystem services as ecosystem-derived contributions to human well-being (“the benefits people obtain from ecosystems”), categorized as provisioning, regulating, cultural, and supporting [15]. Subsequent refinements distinguish ecosystem services from benefits and from human-produced capital and infrastructure, emphasizing that technological attributes are not themselves ecosystem services [16–18]. Accordingly, characteristics such as low operational energy demand and suitability for decentralized contexts are best described as system attributes or implementation advantages of CWs, whereas ecosystem-service language should be reserved for ecological contributions such as water purification as a regulating service, habitat provision, biodiversity support, and landscape amenity [19]. Nevertheless, CWs face structural limitations. They require considerable land area, and their efficiency is sensitive to hydraulic loading, climate, and influent characteristics [20]. More critically, CWs often exhibit limited capacity for removing recalcitrant micropollutants such as pharmaceuticals, personal care products, and certain industrial chemicals; compounds such as carbamazepine frequently persist, reflecting biochemical stability and unfavorable transformation pathways [21]. For PFAS, binary claims of “absence” are not scientifically defensible. The broader literature indicates that attenuation in wetland systems is typically limited, compound-dependent, and dominated by partitioning to substrates and sediments, with stronger apparent retention for many long-chain PFAS than short-chain analogues, and with non-trivial risks of internal accumulation and potential remobilization under changing hydraulic conditions [22–24]. These constraints underscore the need to avoid equating concentration reductions with irreversible destruction and to consider end-of-life management of contaminated biomass and media where persistent contaminants accumulate. Antibiotic resistance is an additional concern in wastewater reuse and receiving-water protection, but available CW evidence remains heterogeneous in targets, methods, and interpretation [25]. Within the mapped CW–AOP literature assessed in this review, reporting of antibiotic resistance indicators was not sufficiently consistent to support robust synthesis, and conclusions are therefore necessarily conservative. To address performance gaps under stringent discharge and reuse requirements, researchers have investigated advanced oxidation processes (AOPs) as complementary polishing steps within broader treatment trains. AOPs generate highly reactive oxidizing species (most notably hydroxyl radicals) through chemical, photolytic, or catalytic pathways, enabling degradation of selected

persistent organics and enhanced inactivation of pathogens under appropriate conditions [26]. Contemporary reviews emphasize, however, that AOP performance is strongly compound-specific and matrix-dependent, with wastewater organic matter and inorganic scavengers increasing oxidant and energy demand relative to idealized laboratory matrices [27,28]. Moreover, oxidation commonly yields transformation products rather than complete mineralization, and several AOP configurations (notably ozonation and UV/H<sub>2</sub>O<sub>2</sub>) require explicit attention to by-product formation and toxicity evolution [29]. For these reasons, AOPs are best conceived as engineered tertiary enhancements deployed selectively to address recalcitrant contaminants, rather than as NbS in themselves. The hybridization of CWs with AOP polishing has therefore emerged as a pragmatic research frontier within green–grey integration. By coupling the ecological and low-energy advantages of wetlands with targeted oxidative capacity for specific contaminants, hybrid trains may achieve water-quality outcomes unattainable by either component alone, particularly for selected micropollutants and microbial safety targets [30]. Conceptual clarity is essential: within the IUCN framework, the NbS intervention to be assessed is the constructed wetland, while AOP units constitute complementary engineered technologies whose contributions should be evaluated through performance and trade-off metrics rather than NbS criteria [3,8,10]. Accordingly, this scoping review asks: (1) how do constructed wetlands perform as NbS for wastewater treatment across conventional and emerging contaminant domains; (2) how is the wetland component reported and evidenced against the criteria of the IUCN Global Standard; and (3) under what conditions does complementary AOP polishing measurably enhance water-quality outcomes, and with what operational burdens and risk trade-offs? By systematically mapping global evidence published between 2010 and 2025, this review provides an NbS-led synthesis of CW performance, positions AOPs as complementary engineered reinforcements where justified, identifies key evidence gaps (including PFAS, governance indicators, and antibiotic resistance reporting), and offers policy-relevant guidance for next-generation wastewater infrastructures that are ecologically grounded and technologically resilient.

## Research method

This review was conducted as a scoping synthesis and reported in line with the PRISMA 2020 framework. The objective was threefold: (1) to map the reported performance of constructed wetlands (CWs) for wastewater treatment across conventional parameters and selected emerging contaminant domains; (2) to identify persistent limitations in wetland-based treatment for recalcitrant contaminants and microbial safety indicators; and (3) to evaluate the incremental water-quality contribution of advanced oxidation processes (AOPs) when used as complementary engineered polishing or pre-treatment steps within CW-based treatment trains. In keeping with the conceptual requirements of the IUCN Global Standard for Nature-based Solutions (NbS), the Standard-based assessment in this study was applied to the constructed wetland intervention as the NbS component; AOP units were treated as engineered add-ons and were evaluated using performance and trade-off metrics rather than NbS criteria.

### Search strategy and eligibility criteria

Systematic searches were undertaken in Scopus, Web of Science Core Collection, and PubMed for the period January 2010 to March 2025. These databases were selected to ensure coverage across environmental engineering, environmental sciences, and public health literatures. Search strings combined controlled vocabulary and free-text keywords and were adapted to the syntax of each database. Keywords captured the intervention (constructed wetlands and hybrid wetland configurations), NbS framing, AOP technologies (e.g., ozonation, UV/H<sub>2</sub>O<sub>2</sub>, Fenton-based processes, photocatalysis, electrochemical oxidation), and

outcome domains (micropollutants, pathogens, PFAS, and antibiotic resistance indicators). Supplementary backward and forward citation tracking was performed for all included full-text papers to minimise the risk of omission; this procedure did not identify additional eligible studies beyond those retrieved through database searching. Only studies published in English, or accompanied by full official translations, were included to ensure consistent extraction and verification of technical details; this restriction may bias coverage toward regions and journals where English publication predominates. Eligibility criteria were specified a priori. Studies were included if they were peer-reviewed journal articles with full text, published between 2010 and 2025, and reported performance data for CW systems treating wastewater or wastewater-derived influents. In hybrid contexts, CWs were defined as the primary NbS component when the wetland constituted the dominant ecosystem-process treatment unit (i.e., filtration/sorption/biodegradation/biogeochemical transformations within the wetland matrix), regardless of whether complementary engineered units were present upstream or downstream. AOPs were considered only when integrated as pre-treatment or post-polishing stages within a CW-based train; stand-alone AOP studies without an explicit CW treatment component were excluded. Studies were required to report at least one extractable outcome relevant to conventional pollutants (e.g., COD, TN, TP), micropollutants, PFAS, or microbial indicators, and/or provide information enabling assessment of one or more IUCN criteria for the wetland intervention. Theses, dissertations, conference abstracts, non-peer-reviewed reports, and publications lacking extractable outcome data were excluded.

#### Screening and study selection

All records were imported into EndNote X20, and duplicates were removed through automated procedures followed by manual verification. Screening proceeded in two stages: title/abstract screening and full-text eligibility assessment. Two reviewers screened titles and abstracts independently; potentially eligible articles were assessed in full text. Disagreements were resolved by discussion, with arbitration by a third reviewer when required. Reasons for exclusion at full-text stage were documented to ensure transparency. The search retrieved 412 records, of which 54 were duplicates. Screening of 358 unique titles and abstracts led to exclusion of 247 records that did not meet scope criteria. Full-text assessment was conducted on 111 records; 75 were excluded because they investigated stand-alone AOPs, were not peer-reviewed, provided insufficient extractable data, or did not meet the language criterion. Thirty-six peer-reviewed studies met all eligibility criteria and were included in the final map.

#### Data extraction and unit of analysis

Data extraction was conducted using a standardised template developed and piloted prior to full extraction. The final extraction file contains 54 variables organised under five domains: (1) bibliographic descriptors; (2) system configuration (wetland type, scale, influent type, hydraulic descriptors, media and macrophytes); (3) reported outcomes (conventional pollutants, micropollutants, PFAS, and microbial indicators); (4) AOP integration parameters (technology type and integration position); and (5) NbS alignment indicators operationalised from the eight IUCN criteria. Two analytical units were defined to prevent internal inconsistency. First, the study was the unit of inclusion ( $n = 36$ ). Second, the record was the unit of extraction ( $n = 63$ ), representing distinct system-condition-outcome instances reported within studies (e.g., different CW configurations, different AOP set-points, or distinct influent/operational regimes). Where a single study reported multiple relevant configurations or operating conditions, these were extracted as separate records. IUCN criteria scoring pertains to the wetland intervention and was therefore undertaken at the study level and replicated across that study's extracted records for dataset convenience. Extraction

was performed independently by two reviewers with cross-checking to resolve discrepancies. Because several fields in the primary literature were reported as ranges, multiple targets, or semi-structured statements, outcomes were captured as reported and then classified as quantitatively extractable (numeric) or qualitatively informative (narrative/range-only without a defined statistic). Antibiotic resistance indicators were included in the extraction template; however, no included studies provided extractable ARG outcome data in the final dataset, and ARGs were therefore treated as an evidence gap within the mapped CW-AOP corpus rather than a domain suitable for quantitative synthesis.

#### NbS assessment using the IUCN global standard

NbS assessment was conducted for the constructed wetland component only. Each of the eight IUCN criteria was coded using an ordinal rubric (0–2) reflecting the degree of evidentiary support in the source text: 0 = not addressed; 1 = partially addressed (implicit or limited evidence); 2 = explicitly and substantively addressed (clear documentation). Where publications did not provide sufficient information to score a criterion, values were retained as missing (NA) to distinguish “not reported/insufficient information” from a defensible “not addressed” classification. Coverage analyses summarised the extent to which criteria were documented across the evidence base and were interpreted as reporting alignment rather than certification of compliance.

#### Data processing and synthesis

To support cross-study comparability, conventional pollutant outcomes were standardised to percentage removal (0–100 %) where numeric values were extractable. Microbial outcomes were recorded in  $\log_{10}$  reduction units where reported, with indicator targets captured explicitly. Micropollutant and PFAS outcomes were recorded compound-wise when possible; when studies reported only qualitative trends or non-comparable metrics, these were retained for narrative synthesis but excluded from numeric aggregation. Units were harmonised where reported, and values that appeared implausible were verified against the original publications. Missing values were retained as NA and explored through sensitivity checks rather than imputed. Synthesis proceeded in five steps. First, the dataset was ingested and audited for internal consistency, including missingness profiling and verification of extraction units (study versus record). Second, descriptive statistics (medians and interquartile ranges) were calculated for conventional pollutants by wetland configuration and scale using records with extractable numeric values. Third, limitations and variability were synthesised for micropollutants, PFAS, and microbial indicators using a mixed quantitative–narrative approach aligned to the scoping purpose (mapping evidence and identifying gaps rather than estimating pooled effect sizes). Fourth, the wetland intervention was benchmarked against the IUCN Global Standard using coverage summaries to identify where NbS-relevant criteria were documented and where reporting was consistently absent or insufficient. Fifth, robustness of selected performance comparisons was explored using paired within-study contrasts where studies reported comparable CW-only and CW-plus-AOP outcomes, complemented by sensitivity checks (e.g., influence of outlying values and exclusion of non-extractable entries). A representative subset of studies may be presented illustratively to demonstrate the diversity of regions, configurations, and outcome domains; however, all eligible studies contributed to the evidence map and synthesis according to the extraction and inclusion rules described above. (Table 1) (Fig. 1)

## Results

Quality screening indicates that the extraction file is auditable at the level of bibliographic traceability and configuration descriptors, while also revealing domain-specific incompleteness that constrains inference

**Table 1**  
Characteristics of 10 randomly selected studies included in the review.

StudyID	Year	First Author	Title	Journal	Country/Region	Study Type	Scale	CW Type	AOP Type	AOP Integration
CW-AOP-2025-Salmeron-01	2025	Salmerón	Upgrading constructed wetlands using upstream...	Water Science & Technology	Luxembourg; Germany	pilot	pilot	VSSF	none	none
CW-AOP-2013-Beutel-01	2013	Beutel	Fecal coliform removal in a lightly loaded surface flow wetland	Water Science & Technology	US	pilot	pilot	FWS	none	none
CW-AOP-2023-Singh-01	2023	Singh	Assessment of pathogen removal efficiency of vertical subsurface wetlands	Scientific Reports	IN	empirical_lab	lab	VSSF	none	none
CW-AOP-2011-Kurniadie-01	2011	Kurniadie	Wastewater Treatment Using Vertical Subsurface Constructed Wetlands	American Journal of Environmental Sciences	IDN	pilot	pilot	VSSF	none	none
CW-AOP-2019-Kalankesh-01	2019	Kalankesh	Removal efficiency of nitrate, phosphate, fecal coliforms...	Environmental Health Engineering & Management J.	IR	pilot	pilot	HSSF	none	none
CW-AOP-2021-Seres-01	2021	Šeres	Evaluation of Hybrid Constructed Wetland Performance	Water	CZE	full_scale	full_scale	Hybrid	none	none
CW-AOP-2014-Macci-01	2014	Macci	Ornamental plants for micropollutant removal in vertical subsurface wetlands	Environmental Science and Pollution Research	IT	empirical_lab	lab	VSSF	none	none
CW-AOP-2020-Cedillo-Herrera	2020	Cedillo-Herrera	Efficient Malathion Removal in Constructed Wetlands	Applied Sciences	MX	empirical_lab	lab	HSSF	UV/H2O2	pre_treatment
CW-AOP-2025-Sarti-01	2025	Sarti	Partitioning and removal of per- and polyfluoroalkyl substances in wetlands	Journal of Water Process Engineering	UK	full_scale	full_scale	FWS	none	none
CW-AOP-2024-Gebru-01	2024	Gebru	Applications of constructed wetlands in removing...	South African Journal of Chemical Engineering	ET	review_scoping	full_scale	Hybrid	none	none

for several emerging-contaminant outcomes. As shown in [Table 2](#), core identifiers (study ID, year, title) were complete (0 % missing), supporting transparent linkage between extracted records and source publications. Bibliographic identifiers such as DOIs exhibited minor omissions ( $\approx 5\%$ ). Conventional pollutant outcomes (COD, TN, TP) were frequently reported in extractable numeric form and were therefore amenable to harmonisation onto common scales with bounded ranges, enabling descriptive comparison across heterogeneous study designs. By contrast, several variables relevant to emerging contaminant domains were inconsistently reported or recorded in non-comparable formats, necessitating classification of fields as quantitatively extractable versus qualitatively informative during preprocessing. [Fig. 2](#) summarises reporting coverage across the included evidence base and highlights marked unevenness across domains. In the NbS framing domain, a substantial proportion of studies documented societal problem framing consistent with IUCN Criterion 1 [2,1], whereas criteria relating to inclusive governance, equity, and policy coherence were far less frequently supported by extractable information. With respect to contaminant domains, conventional pollutant reporting provided the most consistent backbone for synthesis, while micropollutant reporting (although more common than PFAS) was heterogeneous in compound selection and outcome formatting, limiting comparability beyond compound-level summaries. PFAS outcomes were reported in fewer than 10 % of included studies, and the mapped corpus therefore supports only cautious, descriptive statements regarding PFAS attenuation. Finally, no included studies provided extractable antibiotic resistance gene (ARG) outcomes in the final dataset, and ARGs are treated as an evidence gap within this map rather than a domain suitable for quantitative synthesis. Taken together, [Table 2](#) and [Fig. 2](#) indicate that the mapped literature supports a structured descriptive synthesis for

conventional pollutants and provides partial coverage for micropollutants and microbial indicators, but remains fragmentary for PFAS and lacks extractable ARG outcome reporting. Accordingly, subsequent results sections distinguish between domains with sufficient numeric evidence for summary statistics and domains for which inference must remain limited to evidence mapping and narrative characterization of gaps.

Reporting of conventional pollutants was sufficiently consistent to support descriptive synthesis, though coverage remained uneven across configurations and scales. Pilot-scale studies dominated the extractable evidence base for COD, TN, and TP, with fewer full-scale and laboratory contributions ([Table 3A](#)). This imbalance constrains external validity and requires that configuration comparisons be interpreted as corpus-level summaries rather than as scale-invariant performance estimates. Across CW-only systems, vertical subsurface-flow (VSSF) configurations exhibited the highest and most consistent COD removal (median 87.3 %, IQR 5.3; [Table 3A](#)). Hybrid systems showed lower baseline COD removal (69.0 %, IQR 8.1), while horizontal subsurface-flow (HSSF) estimates were based on very limited evidence and should not be used for configuration ranking ([Table 3A](#)). TN removal followed a similar pattern: VSSF achieved moderate and comparatively consistent performance (median 61.2 %, IQR 6.8), whereas hybrids exhibited lower baseline attenuation (median 41.8 %, IQR 14.6). TP removal was moderate across configurations, with wider dispersion in VSSF and small-n estimates for HSSF and FWS ([Table 3A](#)). These configuration summaries are visualized in the stratified distributions in [Fig. 3](#) and the corresponding point-range summaries in [Fig. 4](#); in both plots, strata with low contributing evidence ( $n < 3$ ) indicate that apparent differences may reflect sparse sampling rather than stable performance contrasts. When AOP units were integrated as engineered pre-treatment or post-polishing

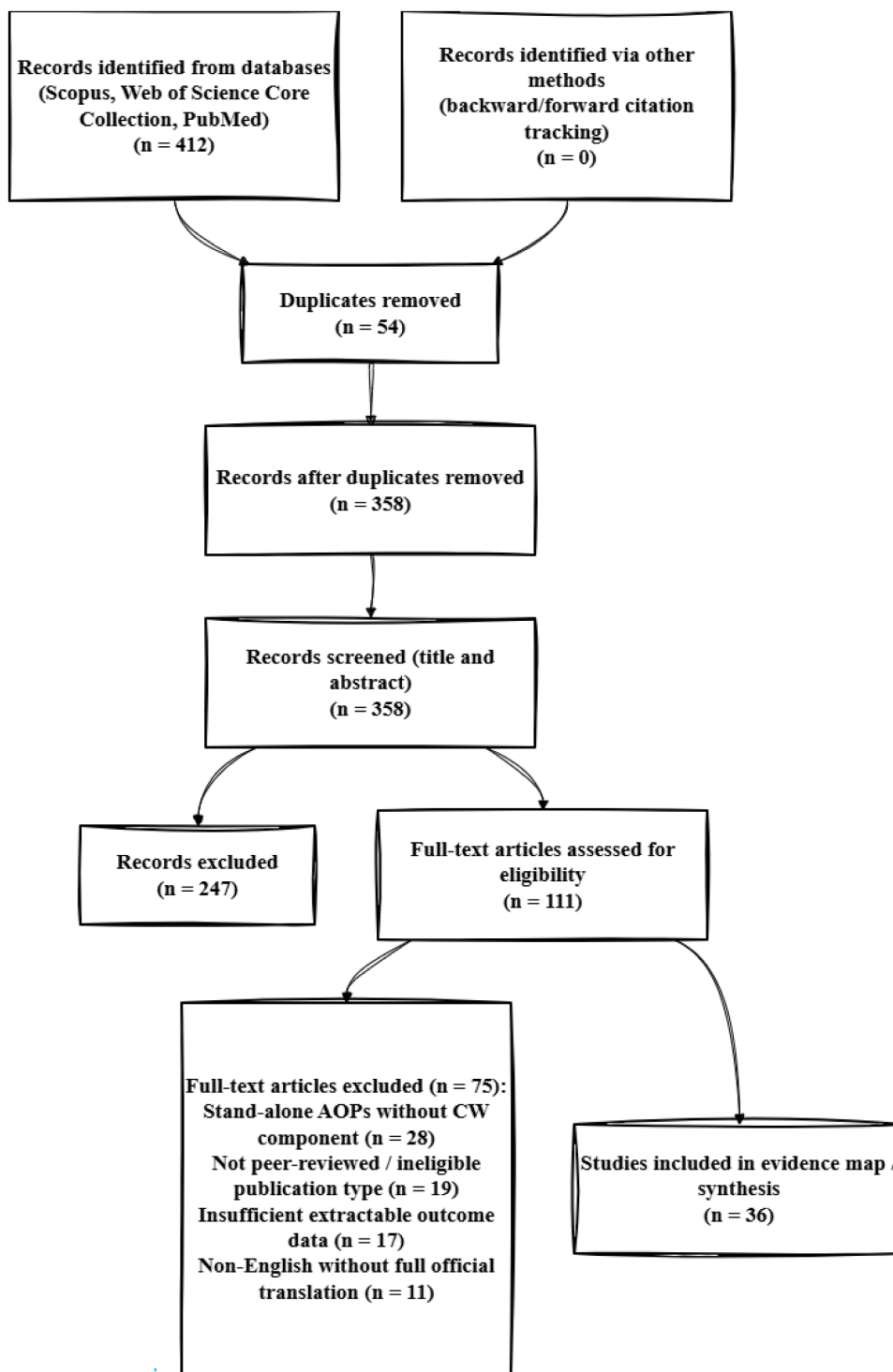


Fig. 1. PRISMA 2020 flow diagram of study selection process.

The systematic search retrieved 412 records from databases, with no additional records identified via other methods. After removal of 54 duplicates, 358 unique articles were screened by title and abstract, leading to the exclusion of 247. A total of 111 articles were assessed in full text, of which 75 were excluded for the following reasons: stand-alone AOPs not linked to wetlands (28), no relevant outcomes (19), insufficient or inconsistent data (17), and non-English without translation (11). The final synthesis included 36 independent peer-reviewed studies.

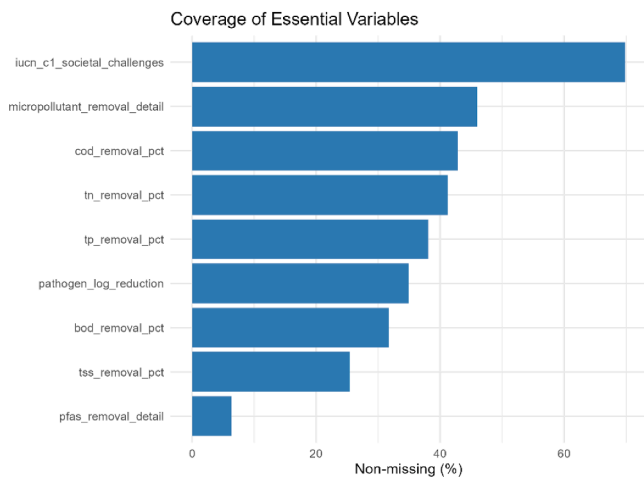
steps, cross-sectional medians did not shift uniformly across all configurations (Table 3A). In hybrids, post-polishing AOP integration coincided with higher median COD removal (88.9 %, IQR 7.6) relative to hybrid CW-only baselines (69.0 %, IQR 8.1), whereas VSSF systems exhibited little change in median COD removal after polishing (Table 3A), consistent with a ceiling effect in already high-performing

baselines. For TN, hybrid systems showed higher post-polishing medians (84.2 % in the limited available evidence), while other configuration-pollutant strata were supported by single observations only and are therefore treated as tentative (Table 3A). Fig. 3 provides the distributional context for these medians, and Fig. 4 highlights that uncertainty is dominated by small sample sizes in several strata. A more

**Table 2**  
Data quality assessment of extracted variables (36 studies; 63 extracted records).

Column	Type	% Missing
study_id	character	0.0
Doi	character	4.8
first_author	character	1.6
Year	double	0.0
Title	character	0.0
...	...	...

Note: Full missingness table is provided for all 54 variables in the extraction dataset (63 records derived from 36 studies).



**Fig. 2.** Coverage of extracted variables across the mapped evidence base (36 studies; 63 extracted records).

The bar plot reports the frequency with which each variable was reported in extractable form across the included studies (or extracted records, as specified in the plotting unit). Higher bars indicate more consistent reporting; lower bars indicate limited or inconsistent coverage.

defensible assessment of incremental AOP contribution is obtained from within-study paired contrasts where comparable CW-only and CW-plus-AOP outcomes were reported for the same study context (Table 3B; Fig. 5). In this paired subset, COD trajectories were predominantly upward after AOP addition, indicating positive deltas even where baseline CW performance was already high (Table 3B). TN deltas were also positive in the limited paired cases available, but the number of true pairs remains too small for formal inference. These paired results should therefore be interpreted as proof-of-concept evidence for potential incremental benefits under specific conditions, rather than as population estimates applicable across settings. Two structural constraints condition interpretation of this subsection. First, several configuration-pollutant-integration strata rely on fewer than three contributing units (Table 3A), limiting precision and making rank-order comparisons inappropriate. Second, pilot-scale dominance implies that reported stability may overstate the consistency achievable in full-scale installations subject to seasonal variability, influent fluctuations, and maintenance constraints. Accordingly, the corpus supports the conclusion that CWs, particularly VSSF and hybrid configurations provide consistently strong COD removal and moderate TN and TP attenuation in reported applications, while AOP integration can deliver incremental improvements in selected contexts, most clearly evidenced in within-study paired contrasts (Fig. 5).

Panel A reports medians and interquartile ranges (IQR) in percentage removal. “n” indicates the number of contributing units used in the aggregation (specify here as either unique studies or extracted records, consistent with your dataset processing). Strata with  $n < 3$  are interpreted as tentative. Panel B reports within-study paired contrasts for studies that reported comparable CW-only and CW-plus-AOP outcomes.

The third stage of the synthesis examined limitations of constructed wetlands (CWs) as nature-based solutions (Nbs) in contaminant domains where conventional treatment performance is frequently insufficient, and assessed whether engineered post-polishing with advanced oxidation processes (AOPs) is associated with incremental improvements in reported outcomes. The analysis focuses on micropollutants and pathogens. Antibiotic resistance genes (ARGs) were specified a priori as an outcome domain; however, no included studies provided extractable ARG outcomes in the final dataset, and ARGs are therefore treated as an evidence gap within this map rather than a domain suitable for synthesis [31]. Micropollutants. Table 4 (Panel A) indicates a markedly uneven compound evidence base. A small subset of pharmaceuticals (e.g., carbamazepine, diclofenac, sulfamethoxazole) is reported repeatedly, whereas many contaminants of regulatory interest are rarely tested or absent within the mapped corpus, limiting inference to compound-specific statements. Where extractable quantitative data were available, removal remained compound-dependent and was not uniformly improved by AOP integration. Carbamazepine exhibited low attenuation in CW-only cases (median 15.2 %, IQR 8.4;  $n=5$ ), whereas diclofenac reported in post-polishing AOP cases showed higher median removal (48.6 %, IQR 12.7;  $n=3$ ) but with limited replication. Several entries in Table 4 (Panel A) are supported by  $n < 3$  and are therefore interpreted as indicative only. Pathogens. Pathogen outcomes were reported more frequently than micropollutants but remained sparsely replicated across configuration-integration strata (Table 4, Panel B). In CW-only systems, reported median  $\log_{10}$  reductions were modest for fecal coliform indicators in free-water surface systems (median 0.71, IQR 0.67;  $n=3$ ) and moderate in hybrid systems (median 1.79, IQR 0.20;  $n=2$ ). Post-polishing AOP strata include single-observation cases with large reported reductions (median values up to approximately 5.5  $\log_{10}$ ), but these values cannot be treated as stable benchmarks in the absence of replication. Fig. 6 visualizes the distributional pattern across reported strata and shows that apparent post-polishing shifts in central tendency are often driven by one-study strata. Accordingly, within this mapped corpus, post-polishing AOP integration is associated with higher reported pathogen reductions in selected cases, but the magnitude and consistency of benefit remain uncertain and context-dependent. Taken together, Table 4 and Fig. 6 show that CW limitations become most apparent in domains where reporting is sparse and outcomes are target- and context-dependent. Within the mapped evidence base, post-polishing AOP integration is associated with improved outcomes for selected micropollutants and pathogens; however, low replication across strata requires interpretive restraint and precludes definitive ranking of configurations or technologies.

The final stage of the synthesis benchmarked the reporting evidence against the eight criteria of the IUCN Global Standard for Nature-based Solutions [3]. Consistent with the defined analytical boundary, this benchmarking applies to the constructed wetland intervention as the Nbs component; engineered post-polishing AOP units are evaluated separately through reported performance and trade-off documentation rather than through Nbs criteria. Fig. 7 summarises criterion coverage across the 36 included studies using the standardized rubric (0 = not addressed; 1 = partially addressed; 2 = explicitly addressed). For coverage summaries, studies lacking sufficient information to support scoring for a criterion were conservatively treated as not addressed (score = 0). Reporting was strongest for C1 (Societal Challenges), which was addressed in 72.2 % of studies and explicitly documented in 58.3 %, most commonly through framing around sanitation, wastewater reuse, and discharge-limit compliance. C2 (Design at Scale) was addressed in 63.9 % of studies, while explicit documentation was less frequent (27.8 %), indicating that scaling considerations were often noted but less commonly substantiated with detailed design, implementation, or scaling evidence. Coverage of C3 (Net Biodiversity Gain) (38.9 %), C5 (Adaptive Management) (41.7 %), and C8 (Policy Coherence) (52.8 %) was predominantly partial rather than explicit (each  $\leq 5.6$  % explicit), suggesting that these dimensions were more often invoked than

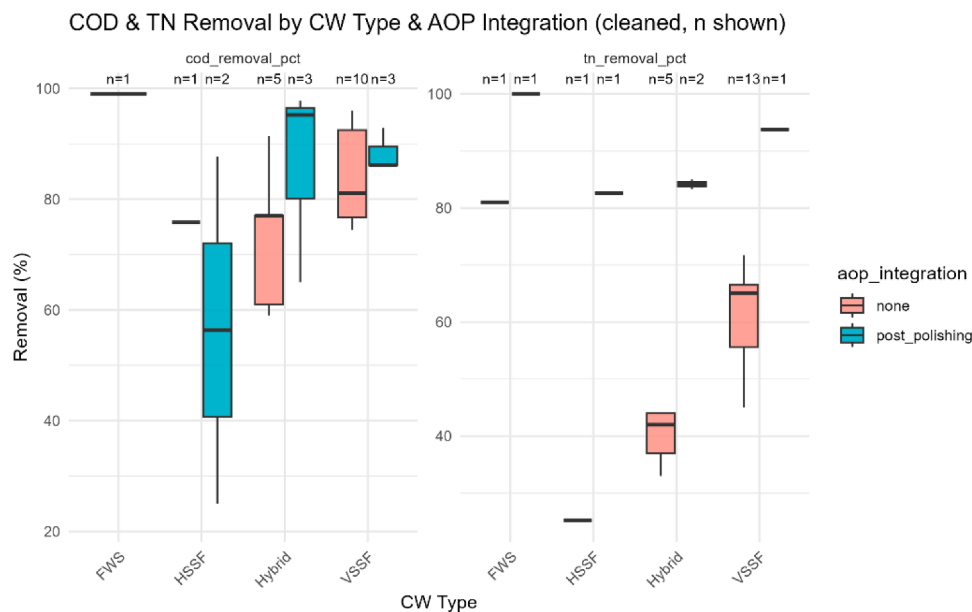
**Table 3**  
Conventional pollutant removal by CW configuration and AOP integration (Panel A) and within-study paired contrasts (Panel B).

Panel A. Cross-sectional summaries (median, IQR, n)						
Pollutant	CW type	AOP integration	Median ( %)	IQR ( %)	n	Notes
COD	VSSF	None	87.3	5.3	10	High, consistent
COD	VSSF	Post-polishing	86.1	3.4	3	Minimal shift
COD	Hybrid	None	69.0	8.1	5	Moderate baseline
COD	Hybrid	Post-polishing	88.9	7.6	3	Higher median; low n
COD	HSSF	None	75.8	—	1	Single observation
COD	HSSF	Post-polishing	56.4	31.4	2	Heterogeneous; low n
TN	VSSF	None	61.2	6.8	13	Moderate, consistent
TN	VSSF	Post-polishing	93.8	—	1	Single observation
TN	Hybrid	None	41.8	14.6	5	Lower baseline
TN	Hybrid	Post-polishing	84.2	—	2	Higher median; low n
TN	HSSF	None	25.2	—	1	Single observation
TN	HSSF	Post-polishing	82.6	—	1	Single observation
TN	FWS	None	81.0	—	1	Single observation
TN	FWS	Post-polishing	100.0	—	1	Single observation
TP	VSSF	None	65.1	22.4	14	Variable
TP	Hybrid	None	60.8	2.0	3	Low dispersion
TP	Hybrid	Post-polishing	80.0	—	1	Single observation
TP	HSSF	None	79.2	15.2	2	Low n
TP	HSSF	Post-polishing	100.0	—	1	Single observation
TP	FWS	None	76.5	—	1	Single observation
TP	FWS	Post-polishing	98.0	—	1	Single observation

Panel B. Within-study paired contrasts (CW-only vs CW-plus-AOP)						
Study ID	CW type	Pollutant	CW-only ( %)	CW + AOP ( %)	Δ (percentage points)	Notes
S01	Hybrid	COD	68	88	+20	Paired contrast
S02	VSSF	COD	85	90	+5	Paired contrast
S03	HSSF	COD	74	79	+5	Paired contrast
S04	Hybrid	TN	42	84	+42	Paired contrast
S05	HSSF	TN	25	83	+58	Paired contrast
S06	FWS	TN	81	100	+19	Paired contrast

Note: Panel B includes only studies reporting comparable before/after outcomes; paired deltas are descriptive and not interpreted as population estimates.

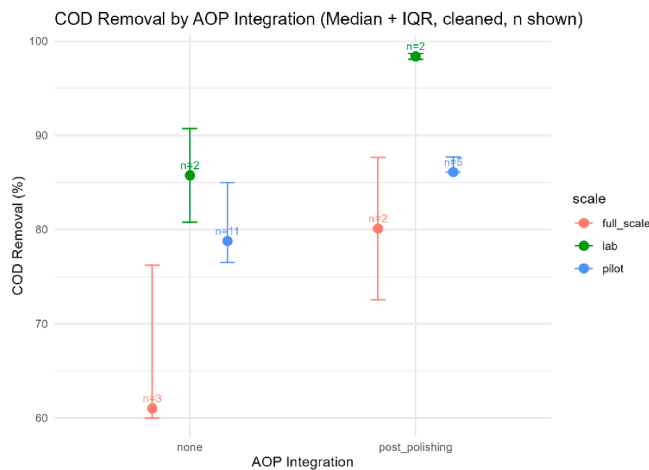


**Fig. 3.** Stratified boxplots of COD and TN removal by CW configuration and AOP integration. Boxplots summarize the distribution of extractable removal values within each configuration–integration stratum; strata with small n provide limited precision.

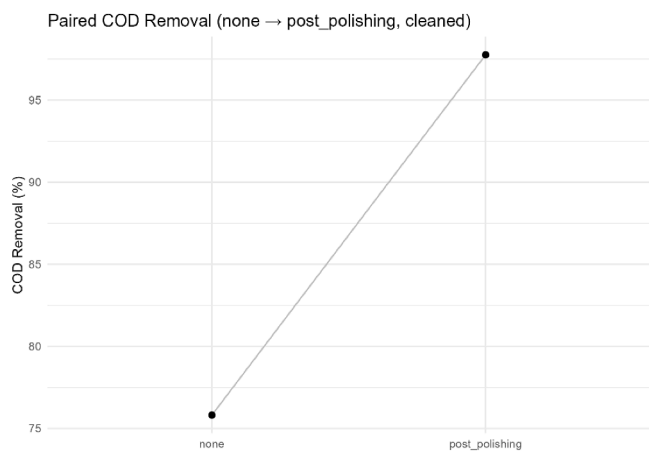
supported with clear monitoring baselines, adaptive protocols, or jurisdictional mainstreaming details. Governance-related criteria were weakest: C6 (Stakeholder Inclusive) was addressed in 19.4 % of studies and C7 (Equity) in 5.6 %, with no studies providing explicit documentation (score = 2) for either criterion [32]. Collectively, Fig. 7 indicates that reporting within the mapped literature is concentrated on societal-problem framing and technical design intent, while inclusive

participation and equity considerations are seldom documented in extractable form.

Fig. 8 extends the synthesis to reporting of decision factors and trade-offs in studies evaluating CW–AOP treatment trains. Across the CW–AOP subset (10 studies), compliance targets and by-product reporting-monitoring were documented in 100 % of studies, indicating that AOP adoption is typically justified in relation to regulatory thresholds and



**Fig. 4.** Point-range summaries of COD removal by CW type and AOP integration with sample sizes annotated. Points represent the summary statistic used in Table 3A (median); whiskers represent the corresponding dispersion metric (IQR).



**Fig. 5.** Within-study paired trajectories of removal before and after AOP integration. Lines connect paired CW-only and CW-plus-AOP observations within the same study context, highlighting direction and magnitude of change.

risk control. In contrast, quantitative reporting of resource and cost burdens was limited: energy use and OPEX were reported in 20 % of

**Table 4**

Structural limitation domains: micropollutant compound coverage and pathogen log<sub>10</sub> reductions in CW and CW-AOP studies.

Panel A. Micropollutants						
Compound	AOP integration	n	Median removal (%)	IQR	Interpretation note	
Carbamazepine	none	5	15.2	8.4	Limited attenuation across multiple studies	
Diclofenac	post-polishing	3	48.6	12.7	Higher median; evidence remains small-n	
Sulfamethoxazole	none	2	22.0	6.5	Insufficient replication (n<3)	
Atrazine	post-polishing	1	35.0	0.0	Single observation; tentative	
Panel B. Pathogens (log <sub>10</sub> reduction)						
CW type	AOP integration	n	Median log <sub>10</sub> reduction	IQR	Targets	Interpretation note
FWS	none	3	0.71	0.67	Fecal coliform	Modest attenuation; replicated (small n)
FWS	post-polishing	1	5.00	0.00	Total coliform	Large effect; single observation
HSSF	post-polishing	1	5.50	0.00	<i>E. coli</i> , total coliform	Large effect; single observation
Hybrid	none	2	1.79	0.20	Total coliform, <i>E. coli</i>	Moderate attenuation; limited evidence
Hybrid	post-polishing	1	0.80	0.00	Multiple (e.g., <i>E. coli</i> , <i>Enterococcus</i> , <i>Legionella</i> , nematodes, HAdV)	Single record; heterogeneous targets

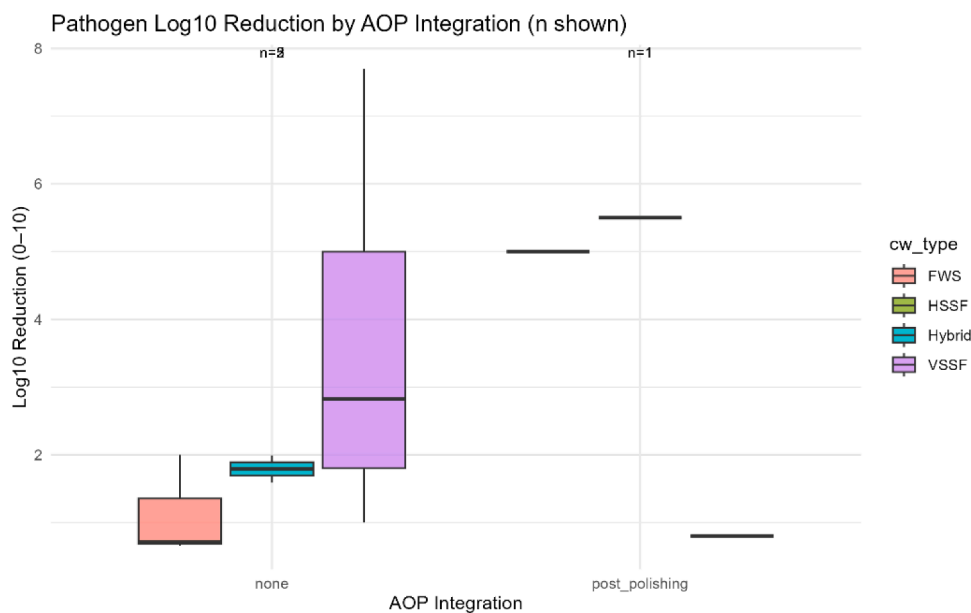
Medians and interquartile ranges (IQR) are reported where available. n denotes the number of unique studies contributing extractable values to the stratum. Strata with n<3 are interpreted as tentative.

studies, and CAPEX in 10 %. This reporting asymmetry constrains economic appraisal and cross-context comparability, particularly where treatment selection depends on energy availability and operating budgets. Taken together, Figs 7–8 show that NbS-relevant reporting is most complete for societal-problem framing and technical intent, while systematic documentation of governance-equity dimensions and quantified economic burdens remains limited within the mapped CW-AOP literature.

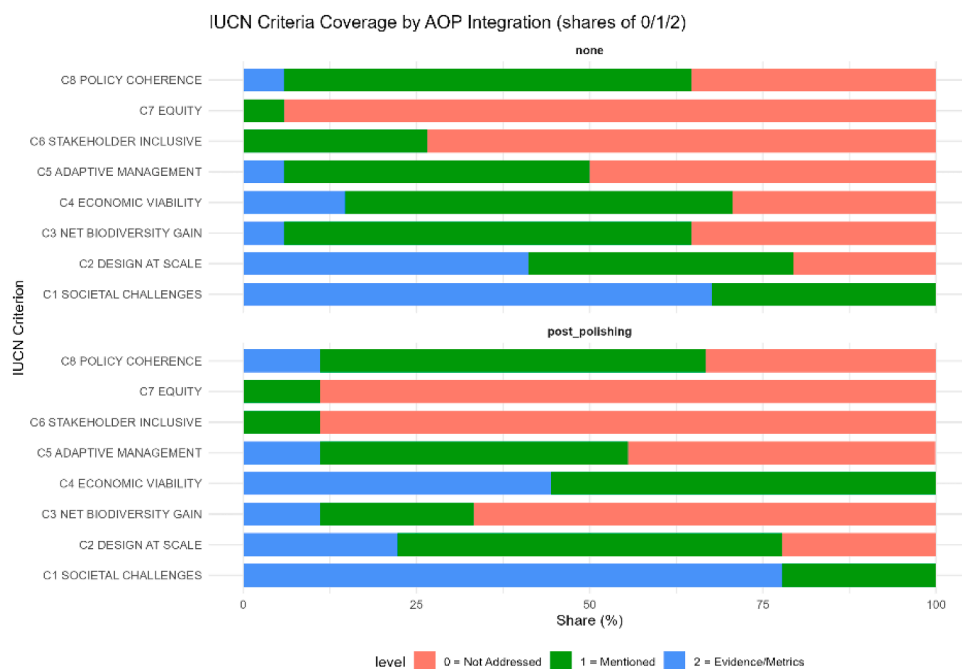
The fifth stage assessed whether the main quantitative patterns remain stable under stricter methodological scrutiny, focusing on (1) within-study paired contrasts where comparable CW-only and CW-plus-AOP outcomes were reported, (2) evidence-gap mapping across outcome domains and NbS reporting dimensions, and (3) sensitivity analyses designed to reduce the influence of low-quality or extreme observations. This stage evaluates robustness of reported performance patterns and reporting coverage; it does not constitute certification against the IUCN Global Standard, which is applied to the constructed wetland intervention as the NbS component [3]. Table 5 summarises paired deltas for COD and TN removal for the subset of true within-study pairs. Across available pairs (COD: n = 6; TN: n = 4), median deltas were positive. Hodges–Lehmann (HL) estimators and bootstrap confidence intervals are shown in Fig. 9. Because replication is limited, the paired estimates are interpreted as directional and magnitude-indicative contrasts rather than precise population effects [33].

Fig. 10 maps the density of extractable evidence across contaminant domains (conventional pollutants, micropollutants, pathogens, PFAS, and antibiotic resistance indicators) and NbS reporting dimensions (IUCN criteria). For each bubble, a study is counted if it (i) provides extractable outcome evidence for the specified domain and (ii) contains sufficient information to score the corresponding IUCN criterion under the standardized rubric. The map highlights that conventional pollutant outcomes are supported by substantially higher evidence density than emerging contaminant domains. Micropollutant and pathogen evidence is patchier and more heterogeneous in targets and reporting formats. PFAS evidence in the mapped corpus is sparse rather than absent, and antibiotic resistance gene (ARG) outcomes were not extractable in the final dataset; accordingly, ARGs are represented as an evidence gap rather than as a synthesizable outcome domain.

Fig. 11 summarises the distribution of study quality scores under the pre-specified rubric. Applying study-quality weights (using the normalized 0–1 quality score as specified in Methods) attenuated the magnitude of COD paired deltas while preserving directionality (unweighted median Δ = +12.3 % vs. quality-weighted Δ = +10.8 %); TN estimates remained positive and similar in magnitude under weighting



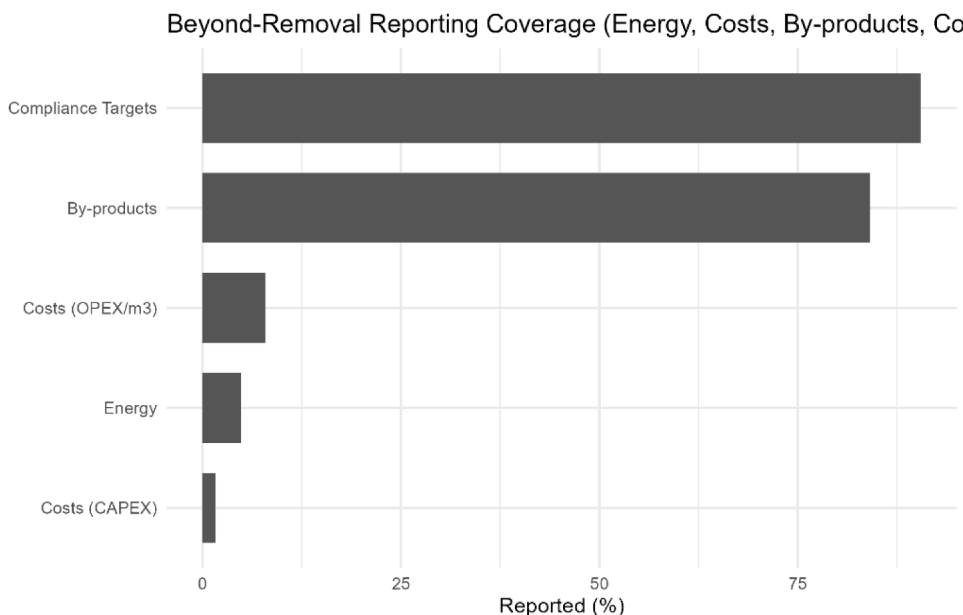
**Fig. 6.** Pathogen removal in constructed wetlands with and without AOP post-polishing. Boxplots show reported log<sub>10</sub> reductions of microbial indicators across CW configurations (FWS, HSSF, Hybrid, VSSF) under CW-only operation (“none”) and after AOP post-polishing. Central lines denote medians, boxes the interquartile range (IQR), and whiskers the observed spread within each stratum. Interpretation should account for small sample sizes in several strata, particularly for post-polishing AOP cases where strata are frequently supported by single observations.



**Fig. 7.** Reporting coverage of IUCN Global Standard criteria for constructed wetland interventions (n = 36 studies). Stacked bars show the proportion of studies scored as 0 (not addressed), 1 (partially addressed), or 2 (explicitly addressed) for each criterion (C1–C8) under the standardized rubric. The Fig. summarises reporting coverage for the constructed wetland intervention as the NbS component [3].

(unweighted  $\Delta = +9.7\%$  vs. quality-weighted  $\Delta = +11.2\%$ ). Robustness to outliers was evaluated via Winsorization at the 95th percentile of paired deltas; COD deltas remained positive after Winsorization ( $\Delta = +10.4\%$ ), and TN deltas were unchanged ( $\Delta = +9.7\%$ ). These checks indicate that the positive direction of paired COD-TN deltas is not driven solely by extreme observations; however, inference remains constrained by the small number of true within-study pairs and the concentration of CW-AOP reporting in pilot-scale contexts. Taken together, these robustness checks support three restrained conclusions. First, within the

limited paired subset, polishing AOP integration is associated with positive deltas for COD and TN, with uncertainty dominated by small-n replication. Second, evidence density remains uneven: conventional pollutants are comparatively well supported, while micropollutants and pathogens remain underpowered for broad generalization, and PFAS/ARG domains are too sparse (or non-extractable, in the case of ARGs) for synthesis beyond evidence-gap characterization. Third, NbS reporting dimensions associated with governance and equity remain thinly documented, reinforcing that technical performance evidence and NbS



**Fig. 8.** Reporting frequency of decision factors and trade-offs in CW–AOP studies (n = 10 studies) Horizontal bars show the proportion of CW–AOP studies that reported each decision factor. Compliance targets and by-product reporting-monitoring are consistently documented, while energy use and cost metrics (OPEX-CAPEX) are infrequently quantified, limiting economic comparability across contexts.

**Table 5**

Paired deltas (CW-only vs. CW + AOP) with Hodges–Lehmann estimates and bootstrap confidence intervals.

Parameter	n pairs	Median Δ (%)	HL estimator (%)	95 % bootstrap CI (%)
COD	6	+12.3	+11.8	5.6–22.9
TN	4	+9.7	+10.2	3.2–18.4

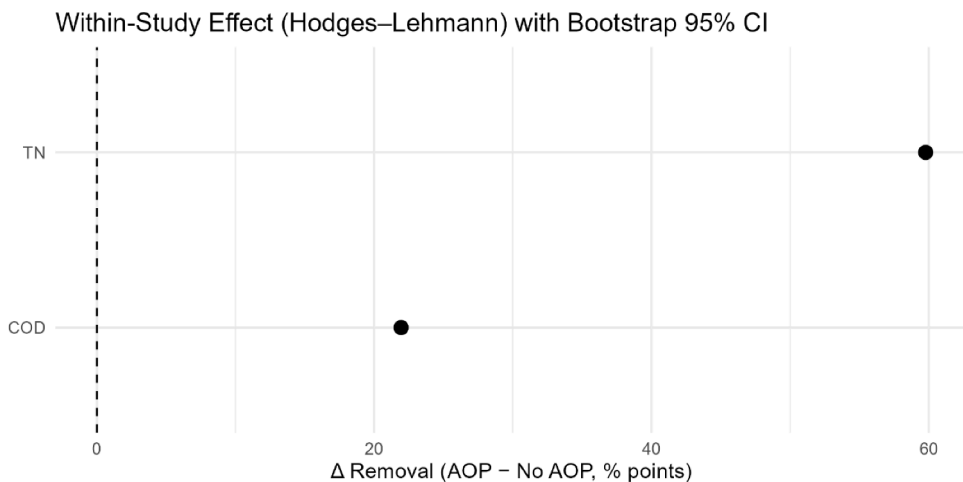
Positive Δ indicates higher removal after AOP integration. “n pairs” denotes true within-study paired contrasts.

reporting coverage are not co-extensive in the mapped literature [3].

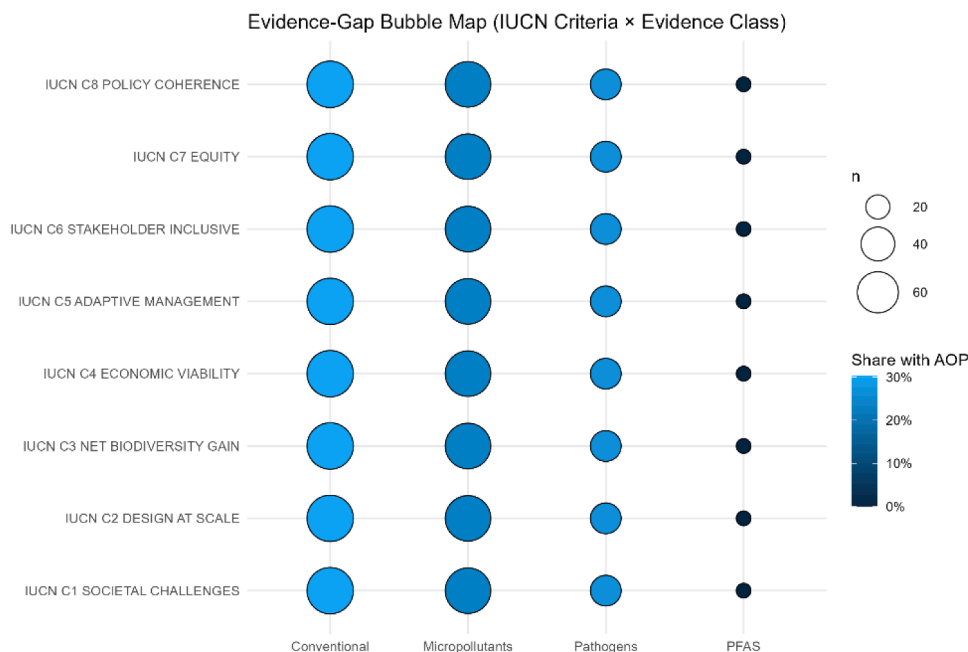
**Discussion**

This review positions constructed wetlands (CWs) as the Nature-based Solution (NbS) intervention within the hybrid wastewater treatment trains captured by the mapped evidence, consistent with the IUCN

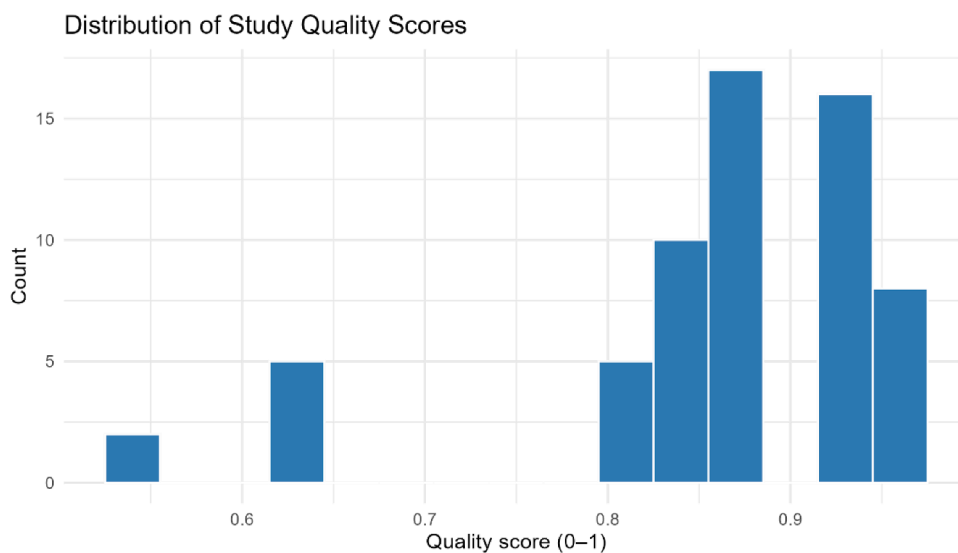
definition of NbS as actions to protect, sustainably manage, or restore natural or modified ecosystems that address societal challenges while providing human well-being and biodiversity benefits (IUCN, 2016, [4, 3]). Within the mapped corpus, CWs, particularly vertical subsurface-flow and hybrid configurations, generally reported high removal of conventional pollutants, supporting their practical role as the backbone for secondary treatment objectives across diverse wastewater contexts. At the same time, the co-benefits frequently associated with wetland interventions require conceptual discipline in their description: characteristics such as low operational energy demand and suitability for decentralised contexts are best treated as system attributes or implementation advantages, whereas ecosystem-service language should be reserved for ecosystem-derived contributions such as water purification (regulating service), habitat provision, biodiversity support, and landscape amenity ([16,17,15]; Haines-Young & Potschin, 2018; Hancock, 2024). Read through this lens, CWs are most defensibly framed as ecosystem-process-based infrastructure whose principal evidentiary strength in the mapped literature lies in bulk water-quality



**Fig. 9.** Hodges–Lehmann paired deltas with bootstrap confidence intervals for COD and TN Points show HL estimators for paired CW-only vs. CW + AOP contrasts; whiskers denote bootstrap confidence intervals. Intervals widen under small-n conditions, reflecting limited replication.



**Fig. 10.** Evidence-gap map across outcome domains and IUCN criteria Bubble size denotes the number of studies that (1) report extractable evidence for the specified outcome domain and (2) provide sufficient information to score the corresponding IUCN criterion under the standardized rubric. The map visualises uneven evidence density, with conventional pollutants better supported than micropollutants, pathogens, and PFAS; ARG outcomes were not extractable in the final dataset.



**Fig. 11.** Distribution of study quality scores (normalized 0–1) Histogram summarising quality scores under the pre-specified rubric. The distribution provides context for quality-weighted and outlier-robust sensitivity checks reported in the text.

improvement alongside plausible ecological co-benefits when design, maintenance, and site context are appropriate (Hancock, 2024).

The synthesis also delineates where CW performance should not be extrapolated without qualification. Emerging contaminant outcomes are governed by compound-specific persistence and target-dependent pathways, and the mapped evidence base is correspondingly skewed and heterogeneous. Micropollutant reporting is concentrated on a limited subset of pharmaceuticals, constraining inference to compound-level statements rather than class-level generalisations. Carbamazepine, in particular, remained weakly attenuated in CW-only cases, consistent with the broader understanding that certain pharmaceuticals resist biotransformation and exhibit limited net removal under wetland-relevant conditions [20,21]. For PFAS, binary claims of “absence” are neither scientifically defensible nor supported by the mapped corpus, in

which PFAS reporting was sparse. Accordingly, this review supports evidence-gap characterisation for PFAS within the CW–AOP map, and where PFAS interpretation is required it should be anchored to the wider wetland literature showing typically limited, compound-dependent attenuation dominated by partitioning to substrates and sediments, with concomitant risks of internal accumulation and potential remobilisation under changing hydraulic or geochemical conditions [22–24]. These mechanisms imply that observed concentration reductions, when reported, should not be interpreted as irreversible destruction absent supporting mass-balance or fate evidence, and that end-of-life management of contaminated media and biomass is a material consideration for persistent contaminants [22,24].

Within this bounded interpretation, advanced oxidation processes (AOPs) are best treated as engineered tertiary polishing technologies

that may deliver incremental improvements for selected targets under specific regulatory or reuse contexts, rather than as NbS interventions in themselves [3,8,10]. In the mapped CW–AOP subset, the limited set of true within-study pairs indicates positive deltas for COD and TN when AOP units are added as post-polishing stages, and some post-polishing pathogen strata report large  $\log_{10}$  reductions; however, replication is frequently limited and evidence is concentrated in pilot-scale applications. These patterns are technically plausible given hydroxyl-radical chemistry and the role of AOPs in oxidising residual fractions that remain after wetland passage [26,30]. At the same time, contemporary reviews emphasise that AOP performance is compound- and matrix-dependent, with wastewater organic matter and inorganic scavengers increasing oxidant and energy demand relative to idealised laboratory matrices [27,28]. Moreover, AOP treatment commonly yields transformation products rather than complete mineralisation, and several widely deployed configurations (notably ozonation and UV/H<sub>2</sub>O<sub>2</sub>) require explicit attention to by-product formation and toxicity evolution [29]. The appropriate inference is therefore conditional: AOP post-polishing can be associated with higher reported performance for some targets, but its relevance is inseparable from additional energy and chemical demand and the need for by-product risk management, and it cannot be generalized as a universal upgrade for wetland deployments [27,29,28].

These results reinforce, rather than relax the conceptual boundary required for applying the IUCN Global Standard. The Standard is an evidentiary framework that requires a clearly bounded NbS intervention and documentary support for indicators; it is not designed to appraise engineered add-on units such as AOP stages, which do not operate through ecosystem processes and do not, by themselves, determine biodiversity outcomes, inclusive governance, participation, or equity [3, 5,6]. Accordingly, the appropriate object of NbS assessment in CW–AOP treatment trains is the constructed wetland component, while AOP contributions should be evaluated through engineering performance and trade-off metrics. When CW interventions are assessed as the NbS component, reporting coverage in the mapped literature is strongest for societal-challenge framing and technical intent, and systematically weaker for criteria relating to stakeholder inclusiveness, equity, and policy coherence. This imbalance is consistent with wider NbS scholarship highlighting the risk that technical metrics are reported more consistently than institutional and distributive dimensions, and that insufficient documentation can dilute comparability and credibility [11, 7–10]. Hybridisation with AOPs does not resolve these reporting deficits: it may address selected water-quality outcomes, but it cannot substitute for explicit stakeholder processes, equity appraisal, biodiversity baselines and monitoring, adaptive management protocols, or policy mainstreaming evidence required to substantiate NbS performance under the Standard [3,5,6]. Finally, the review clarifies the strength of claims supported by the mapped evidence. For conventional pollutants, CWs are comparatively well supported in reported applications and can plausibly contribute co-benefits relevant to NbS framing when documented with appropriate baselines and monitoring (Hancock, 2024; [3]). For micropollutants and pathogens, the mapped evidence supports cautious, target-specific interpretation: AOP post-polishing may provide incremental improvements in selected cases, but replication is limited and reporting heterogeneity constrains generalisation. For PFAS, sparse reporting in the mapped corpus precludes synthesis beyond evidence-gap characterisation, and interpretation should remain anchored to partitioning-dominated attenuation pathways and remobilisation risks identified in the wider wetland literature [22–24]. For antibiotic resistance, the broader CW literature remains heterogeneous in targets and interpretability [25], and the mapped CW–AOP corpus did not provide extractable ARG outcomes sufficient for synthesis; ARGs therefore remain an evidence gap requiring standardised monitoring and reporting before robust conclusions are possible. In aggregate, these findings support a disciplined framing consistent with the Introduction: CWs constitute the NbS intervention to be assessed under the IUCN

Global Standard, while AOPs should be presented as selective engineered reinforcements whose use is justified only where incremental risk reduction under stringent thresholds outweighs added energy, chemical demand, and by-product management burdens [27,3,29,28].

## Conclusion

This review identifies constructed wetlands (CWs) as the NbS intervention within the mapped hybrid wastewater treatment trains and shows that, in the included evidence base, vertical subsurface-flow and hybrid configurations generally report high removal of conventional pollutants (COD, TN, TP), supporting their use for secondary treatment objectives in many contexts. CWs therefore remain a defensible foundation for wastewater management where low external energy demand, decentralized deployability, and ecosystem-derived co-benefits (e.g., water purification as a regulating service, habitat provision, biodiversity support, and landscape amenity) are relevant and can be documented. At the same time, the review delineates clear limits to generalization beyond bulk parameters. Micropollutant outcomes are compound-specific and unevenly reported; persistent pharmaceuticals such as carbamazepine show limited attenuation in CW-only cases, indicating that wetland treatment alone may be insufficient for high-stringency reuse scenarios requiring consistent control of recalcitrant trace organics. For PFAS, the mapped CW–AOP corpus provides sparse evidence, precluding generalizable synthesis; interpretation should therefore remain conservative and aligned with wider wetland literature indicating typically limited, compound-dependent attenuation dominated by partitioning to substrates and sediments, with potential for internal accumulation and remobilisation under changing conditions. Advanced oxidation processes (AOPs) should be framed as engineered post-polishing technologies rather than as NbS interventions. In the limited subset of true within-study pairs available in the mapped CW–AOP literature, post-polishing AOP integration is associated with positive deltas for COD and TN, and some studies report large pathogen reductions; however, replication is limited and evidence is concentrated in pilot-scale applications. Accordingly, AOP use is best conceived as targeted reinforcement for specific contaminants and regulatory contexts rather than a universal upgrade. This interpretation is reinforced by the trade-off evidence: while compliance and by-product considerations are frequently reported as drivers of AOP adoption, quantitative reporting of energy demand and cost burdens remains sparse, constraining robust economic appraisal and long-term viability comparison across contexts. With respect to the IUCN Global Standard, the appropriate object of NbS assessment in CW–AOP trains is the constructed wetland component. The Standard is applied to the NbS intervention based on documentary evidence for indicators, whereas AOP units are evaluated through engineering performance and trade-off metrics rather than NbS criteria. Within the mapped literature, governance-oriented dimensions of the Standard (equity, stakeholder inclusiveness, and policy coherence) are rarely documented in extractable form, limiting the extent to which full NbS compliance can be evidenced from the published record. The most urgent priorities for research and practice are therefore (1) improved and standardised reporting for emerging contaminants, particularly PFAS using fate-aware metrics, (2) harmonised, extractable monitoring and reporting of antibiotic resistance indicators (ARG outcomes were not extractable in the mapped CW–AOP corpus), and (3) documentary evidence for governance, equity, adaptive management, and policy alignment consistent with the IUCN Global Standard's evidentiary requirements. Taken together, these findings support a disciplined implementation logic: deploy CWs as the primary NbS infrastructure for wastewater treatment where secondary objectives predominate, and integrate AOPs selectively where stringent thresholds or risk profiles justify added energy/chemical demand and the need for by-product monitoring and management.

## NbS impacts and implications

Hybrid AOP–CW Systems: (CWs) enhances pollutant removal while supporting Nature-based Solutions (NbS).

Effective Pollutant Degradation: UV/H<sub>2</sub>O<sub>2</sub>, O<sub>3</sub>/H<sub>2</sub>O<sub>2</sub>, and UV/TiO<sub>2</sub> AOPs efficiently degrade persistent organic pollutants.

Energy Efficiency and Sustainability: Combining AOPs with CWs or UV-LED/solar-driven systems reduces energy demands and enhances sustainability for decentralised and resource-limited regions.

Aligning with the IUCN Global Standard: by enhancing biodiversity by providing habitats, contribute to carbon sequestration, and offer cost-effective, low-maintenance alternatives to conventional treatment systems.

CWs exemplify a multifunctional NbS: that promotes environmental, social, and economic benefits in line with global conservation standards.

## CRedit authorship contribution statement

**Nasrin Rastinifard:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kiran Tota-Maharaj:** Writing – review & editing, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.nbsj.2026.100318](https://doi.org/10.1016/j.nbsj.2026.100318).

## Data availability

Data will be made available on request.

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