Influencia del tipo de sustrato en la eficiencia de humedales construidos de flujo subsuperficial horizontal y vertical para el tratamiento de aguas residuales domésticas

Influence of substrate type on the efficiency of horizontal and vertical subsurface flow constructed wetlands for the treatment of domestic wastewater

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Abstract

This systematic review (Scopus, 2015–2024) and bibliometric analysis assess the influence of substrate in subsurface constructed wetlands (horizontal and vertical) for treating domestic wastewater. Nine media were compared: gravel, zeolite, biochar, steel slag, volcanic rock, expanded clay (LECA), laterite, ceramic/brick, and sugarcane bagasse. Evidence indicates that the granular matrix not only provides structural support but also governs filtration, adsorption/ion exchange, precipitation (P), and biofilm development, thereby conditioning BOD/COD and nitrogen removal. For phosphorus, steel slag, laterite, and ceramic outperform inert media; for nitrogen, biochar and bagasse supply carbon for denitrification, while zeolite enhances ammonium retention. A stratified design is proposed with replaceable reactive layers (for P) and carbon amendments (10–30%) for N, tailored to local objectives and resource constraints. Bibliometric mapping shows growth since 2018 and an emphasis on alternative substrates and process intensification. The study concludes that strategic selection and layering of substrates can match or surpass classical design variables.

Keywords: wastewater treatment, constructed wetlands, zeolite, wetland bed.

Resumen

Esta revisión sistemática (Scopus, 2015–2024) y análisis bibliométrico evalúan la influencia del sustrato en los humedales construidos de flujo subsuperficial (horizontal y vertical) para el tratamiento de aguas residuales domésticas. Se compararon nueve medios filtrantes: grava, zeolita, biocarbón (biochar), escoria de acero, roca volcánica, arcilla expandida (LECA), laterita, materiales cerámicos/ladrillo y bagazo de caña de azúcar. La evidencia indica que la matriz granular no solo proporciona soporte estructural, sino que también regula los procesos de filtración, adsorción/intercambio iónico, precipitación (P) y desarrollo de biopelículas, condicionando así la remoción de DBO/DQO y nitrógeno. En cuanto al fósforo, la escoria de acero, la laterita y los materiales cerámicos presentan un desempeño superior al de los medios inertes; para el nitrógeno, el biocarbón y el bagazo aportan carbono para la desnitrificación, mientras que la zeolita mejora la retención de amonio. Se propone un diseño estratificado con capas reactivas reemplazables (para fósforo) y enmiendas carbonosas (10–30 %) para nitrógeno, adaptado a los objetivos locales y a las limitaciones de recursos. El mapeo bibliométrico evidencia un crecimiento sostenido de las investigaciones desde 2018, con énfasis en sustratos alternativos y la intensificación de procesos. El estudio concluye que la selección estratégica y la disposición en capas de los sustratos pueden igualar o superar la influencia de las variables clásicas de diseño.

Palabras clave: tratamiento de aguas residuales; humedales construidos; zeolita; lecho de humedal.

Introduction

HCS replicate natural wetland processes and have proven effective, robust, and low-cost for decentralized sanitation (Kadlec & Wallace, 2009; Vymazal, 2018). Functionally, the substrate is a major determinant of performance: it provides root support, high specific surface area for biofilms, and active sites for sorption/precipitation reactions (García et al., 2010; Wu et al., 2015; Langergraber, 2013). Although gravel/sand remain the standard due to availability and hydraulic stability, their limited phosphorus capacity compels the exploration of reactive media (Weber & Drizo, 2021). Over the past decade, there has been a shift toward enriched or valorized substrates—zeolite for ammonium (cation exchange), biochar for adsorption of organics and denitrification (carbon supplementation), steel slag and laterite for phosphates (precipitation/adsorption on Ca/Fe/Al), and volcanic rock/pumice as multifunctional porous supports—which, when properly combined and coupled to hydraulic retention time (HRT) and aeration, can overcome the limits of inert media (Wang et al., 2024; El Barkaoui et al., 2023; Zhang et al., 2022; de Rozari et al., 2021; Jethwa et al., 2017). This manuscript comparatively evaluates the influence of substrate in HCS (2015–2024) and synthesizes the field's bibliometric trends (Scopus only).

Methodology

PRISMA 2020 was followed (Page et al., 2021). The Scopus search (2015–2024, English/Spanish) used: "constructed wetland*" AND (substrate OR media OR fill) AND (gravel OR sand OR zeolite OR biochar OR "steel slag" OR pumice OR laterite) AND ("domestic wastewater" OR sewage). Inclusion criteria: subsurface flow constructed wetlands (HF/VF) with domestic wastewater; explicit evaluation of the substrate; quantitative metrics (BOD/COD/N/P/coliforms); peer-reviewed. Exclusion: surface-flow systems, non-extrapolable industrial matrices, absence of comparable data. A total of 420 records were identified, with 102 duplicates; after screening/abstracts and full texts, 52 were included. For each study, the following were extracted: substrate, HF/VF configuration, HRT, loadings, vegetation, and removal efficiencies; due to heterogeneity, a comparative descriptive synthesis (weighted typical ranges) was performed. The bibliometric analysis (Scopus only) characterized annual volume and keyword co-occurrence (threshold ≥5) using VOSviewer.

Results

In general, gravel/sand achieve 75–90% BOD/COD under appropriate designs, with NH_4^+ removal of 60–80% in VF and TP of 10–30%. Zeolite markedly increases NH_4^+ removal (84–99%) and enables TN >80% when coupled with anoxic zones. Biochar raises BOD/COD (85–95%) and improves TN (60–85%) through adsorption and carbon supply for denitrification; NO_3^- often decreases by ~60–75% in VF with 15–25% biochar. Steel slag and laterite excel for TP (≥60–>90%); with slag, high initial alkalinity can penalize nitrification unless blended with aggregates and vegetation. Pumice/volcanic rock maintains 80–90% COD and 70–85% NH_4^+ with TP 50–70%, offering good microbial support and moderate costs (depending on local availability).

Table 1. Typical efficiencies by substrate (synthesis, 2015–2024).

Substrate	BOD_5 (%)	COD (%)	NH_4^+-N (%)	TN (%)	TP/ PO_4^{3-} (%)	Notes	References
Gravel/sand	75–90	75–90	60–80 (VF)	50–75	10–30	Robust; low P capacity	(Ntountounakis et al., 2025a)
Zeolite	60–85	50–85	84–99	80–92	20–40	Excellent for NH_4^+; use in blends	(Yang et al., 2023)
Biochar	85–95	85–93	70–95*	60–85	20–50	Adsorption + C for denitrification	(Y. Zhang et al., 2021)
Steel slag	75–90	75–90	40–70	40–65	70–>90	Very high P removal; monitor pH and blend	(Barca et al., 2013)
Volcanic rock/pumice	80–90	80–90	70–85	60–80	50–70	Porous support; local alternative	(de Rozari et al., 2021)
Laterite	75–85	75–85	55–70	55–70	60–70	P adsorption (Fe/Al)	(Menon & Holland, 2013)

In VF with biochar + intermittent aeration, very high NH_4^+ removal has been observed due to combined adsorption/nitrification effects.

In mixtures, Table 2 synthesizes common configurations and conditions. Gravel+sand (VF), with granulometric stratification and HRT of 2–3 days, enhances nitrification and reaches 85–95% COD removal. Gravel+zeolite exceeds 85% NH_4^+ and TN >80% if an anoxic stage is added or HRT is increased (1–3 days). Gravel+biochar (±zeolite) shows adsorption–biological synergy; with HRT of 2–3 days, COD removals of 90–100% and consistent TN improvements are reported.

Table 2. Recommended blends and operating conditions.

Substrate	BOD_5 (%)	COD (%)	NH_4^+-N (%)	TN (%)	TP/ PO_4^{3-} (%)	Notes	References
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Laterite	75–85	75–85	55–70	55–70	60–70	P adsorption (Fe/Al)	(Menon & Holland, 2013b; Sharma et al., 2014; Zheng et al., 2015)

In the bibliometric analysis (Scopus), sustained growth is observed since 2018 with peaks in 2020–2024; the most frequent emerging keywords were biochar, steel slag, zeolite, and emerging contaminants, along with intensification strategies (intermittent aeration, bioelectrochemical hybrids). China, India, and Spain stand out for publication volume and citations (Wang et al., 2024).

Discussion

The results confirm that the substrate governs contaminant-transformation pathways by shaping biofilm structure and redox gradients (Langergraber, 2013; Wu et al., 2015). In wetlands with inert media, organic matter removal depends on filtration and aerobic/anoxic biodegradation; however, phosphorus retention is intrinsically low unless reactive sites are incorporated (Weber & Drizo, 2021). The adoption of enriched media directly addresses this limitation: zeolite increases ammonium retention via cation exchange, stabilizing nitrification (He et al., 2017) and raising TN when an anoxic zone and available carbon are present (through blends or biochar). Biochar, in turn, combines adsorption of organics with carbon provision for denitrification, improving TN in influents with low C/N ratios; it also buffers load shocks thanks to its high specific surface area (El Barkaoui et al., 2023; Panghal et al., 2024). For phosphorus, steel slag and laterite offer sustained sorption/precipitation capacity (Ca–P; Fe/Al–P), achieving efficiencies that far exceed gravel (Zhang et al., 2022; Jethwa et al., 2017). Nevertheless, slag elevates pH and can inhibit nitrification if used alone; hence the recommendation to blend it with neutral aggregates and maintain vegetation that moderates the microenvironment (Zhang et al., 2022). Volcanic rock/pumice provides a porous structure, high surface area, and roughness that promote microbial colonization and solids retention, yielding consistent improvements in COD and NH_4^+ relative to smoother aggregates (de Rozari et al., 2021).

From an engineering standpoint, three practical messages emerge. First, a modular/stratified design maximizes synergies: layers of slag/laterite at the inlet for TP, followed by a vertical-flow (VF) bed with sand+gravel (intermittent aeration) for nitrification, and a zone with biochar for denitrification and COD polishing; this spatial logic avoids antagonisms (e.g., high slag pH impacting nitrifying microflora). Second, HRT should be tuned to the limiting contaminant: 1–3 days are usually sufficient for BOD/N in well-aerated VF systems, whereas ≥5 days allow one to exploit the saturable capacity of media for TP (Weber & Drizo, 2021). Third, operational risks must be managed: (i) clogging with very fine grain sizes (fine laterite/pumice or unwashed biochar), mitigated by stratification and prefiltration; (ii) saturation of reactive capacity (for TP), which requires periodic monitoring and partial replacement; and (iii) alkalinity with slag, addressable through blending and media maturation (Zhang et al., 2022; Weber & Drizo, 2021).

These findings align with the Scopus bibliometrics (Wang et al., 2024): the research community is converging on reactive/valorized substrates and hybrid configurations, with growing attention to emerging contaminants. Future research is trending toward functionalized media (e.g., Fe/Al/Ca-doped biochar, granular iron sulfide) that enable simultaneous N and P removal and, in parallel, recovery of P as a resource.

Conclusions

Substrate selection is a design lever as influential as HRT or flow type, determining the overall efficiency of subsurface constructed wetlands (HCS). (2) Gravel/sand ensure robustness for BOD/COD removal but require amendments if the goal is TP reduction. (3) Zeolite and biochar enhance NH_4^+/TN removal through complementary mechanisms, while steel slag and laterite maximize TP with proper pH and clogging management. (4) Blends (gravel+zeolite; gravel+biochar; gravel+sand in VF) allow tuning of the system to the limiting contaminant. (5) The bibliometric trend confirms the shift toward reactive and valorized media, consistent with efficiency and cost–benefit goals in rural and peri-urban sanitation.

References

Abedi, T., & Mojiri, A. (2019). Constructed wetland modified by biochar/zeolite addition for enhanced wastewater treatment. *Environmental Technology & Innovation, 16*, 100472. https://doi.org/10.1016/j.eti.2019.100472

El Barkaoui, S., et al. (2023). A critical review on using biochar as constructed wetland substrate/additive. *Ecological Engineering, 190*, 106927. https://doi.org/10.1016/j.ecoleng.2023.106927

de Rozari, P., et al. (2021). The use of pumice amended with sand media in vertical flow constructed wetlands for domestic wastewater. *Heliyon, 7*(7), e07562. https://doi.org/10.1016/j.heliyon.2021.e07562

García, J., Rousseau, D. P. L., Morató, J., Lesage, E., Matamoros, V., & Bayona, J. M. (2010). Contaminant removal processes in subsurface-flow constructed wetlands: A review. *Critical Reviews in Environmental Science and Technology, 40*(7), 561–661. https://doi.org/10.1080/10643380802471076

He, H., Duan, Z., Wang, Z., & Yue, B. (2017). Removal efficiency of CWs filled with zeolite–slag hybrid substrate for rural leachate. *Environmental Science and Pollution Research, 24*(21), 17547–17555. https://doi.org/10.1007/s11356-017-9471-2

Jethwa, K., et al. (2017). Phosphorus retention in lateritic soil constructed wetlands (lab scale). In *World Environmental and Water Resources Congress 2017* (pp. 216–226). https://doi.org/10.1061/9780784482025.025

Kadlec, R. H., & Wallace, S. (2009). *Treatment Wetlands* (2nd ed.). CRC Press. https://doi.org/10.1201/9781420012514

Langergraber, G. (2013). Are constructed treatment wetlands sustainable sanitation solutions? *Water Science and Technology, 67*(10), 2133–2140. https://doi.org/10.2166/wst.2013.093

Page, M. J., et al. (2021). The PRISMA 2020 statement. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

Panghal, V., Singh, A., Arora, D., & Kumar, S. (2024). Biochar-modified constructed wetlands using *Eclipta alba*. *Environmental Science and Pollution Research, 31*(11), 17299–17310. https://doi.org/10.1007/s11356-024-32144-0

Vymazal, J. (2018). Constructed wetlands for wastewater treatment. *Water, 10*(9), 1068. https://doi.org/10.3390/w10091068

Wang, Y., Chen, Y., Lu, S., & Guo, X. (2024). Development and trends of constructed wetland substrates (CiteSpace). *Environmental Science and Pollution Research, 31*(10), 14537–14552. https://doi.org/10.1007/s11356-024-32139-x

Weber, P. A., & Drizo, A. (2021). Phosphorus removal by engineered media in constructed wetlands: A review. *Journal of Environmental Management, 287*, 112322. https://doi.org/10.1016/j.jenvman.2021.112322

Wu, H., et al. (2015). A review on the sustainability of constructed wetlands for wastewater treatment: design and operation. *Bioresource Technology, 175*, 594–601. https://doi.org/10.1016/j.biortech.2014.10.068

Zhang, J., Zou, Y., Yu, X., Ding, S., Yan, J., & Min, Y. (2022). Vegetated steel-slag substrate CWs achieve simultaneous N and P removal. *Frontiers in Environmental Science, 10*, 947783. https://doi.org/10.3389/fenvs.2022.947783