Support and adsorbent materials for anaerobic digestion: enhancing process stability and nutrient control

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Abstract

Anaerobic digestion is a technology applied to wastewater treatment and the production of biogas as a renewable energy source. However, it exhibits limitations in the removal of nutrients such as nitrogen and phosphorus, which can lead to eutrophication. Various support materials have been evaluated for their capacity to stabilize the process, enhance biogas production, and facilitate nutrient adsorption. This literature review analyzed the characteristics, mechanisms of action, efficiency, environmental impact, and economic feasibility of different materials applied in anaerobic digesters. The findings indicate that dual-function materials, those providing microbial support and adsorptive capacity, such as biochar and zeolite, achieve superior overall performance. In conclusion, material selection should consider technical efficiency, the target nutrient to be removed, and local availability, with biochar and zeolite emerging as promising options to optimize anaerobic digestion in sustainable contexts such as Ecuador.

Keywords: Nutrient adsorption. biochar. biogas production. zeolite.

Introduction

Anaerobic digestion is a technology used to treat organic wastes through the action of microorganisms under oxygen-free conditions, generating biogas, a methane-rich mixture with potential as a renewable energy source. Beyond reducing pollutant loads, this process enables waste valorization; however, it exhibits limitations in the removal of nutrients such as nitrogen and phosphorus, which can cause environmental impacts if not retained. To address these limitations, numerous studies have evaluated support materials that function both as microbial substrates and as nutrient adsorbents. Among these, biochar, zeolite, modified bentonite, and combinations with nanoparticles or natural polymers stand out (Cuetos et al., 2016; Pilarska et al., 2025; Shen et al., 2022; Tariq et al., 2023; Zhang et al., 2023). From this perspective, the present study asked: which materials can simultaneously enhance biogas production and nutrient retention? We hypothesized that dual-function materials offer superior technical and environmental performance, particularly in contexts where low cost and sustainability, such as in Ecuador, are priority conditions.

Methodology

This work was conducted as a systematic literature review with a descriptive–comparative design. Scientific articles published between 2012 and 2025 were selected from indexed databases such as ScienceDirect, Scopus, SpringerLink, and Google Scholar. The search included combinations of keywords such as "anaerobic digestion," "support materials," "nutrient adsorption," "biochar," "zeolite," "bentonite," "activated carbon," "perlite," "chitosan," and "nutrient recovery." Inclusion criteria encompassed studies evaluating support materials applied to anaerobic digesters with a focus on nitrogen and phosphorus removal, enhanced biogas production, or process stability. Data collection involved extracting technical, environmental, and economic information from each study, including material type, mechanism of action, adsorption capacity, impact on methanogenesis, and associated costs. Variables were grouped into three dimensions: technical efficiency (nutrient removal, biogas production), environmental impact (origin, reusability, residues generated), and economic feasibility (cost per ton, availability, scalability). Results were organized into comparative tables, and a qualitative analysis was conducted to identify behavioral patterns and materials with the greatest overall potential.

Results and discussion

The bibliographic analysis revealed a wide diversity of materials evaluated as supports in anaerobic digestion, each with distinctive characteristics regarding nutrient-removal efficiency, process stability, and operating cost. Although the literature generally favors multifunctional materials, a clear trend emerged toward hybrid approaches that combine physical, chemical, and biological properties to maximize system performance. For example, perlite doped with chitosan and biochar/zeolite/Fe_3O_4 blends exhibited synergistic effects by integrating adsorption, microbial support, and enhanced electron transfer, leading to significant increases in methane production (Pilarska et al., 2025; Zhang et al., 2023).

With respect to nutrient removal, magnesium-modified bentonite stood out for facilitating struvite precipitation, enabling the simultaneous recovery of nitrogen and phosphorus—an advantage over materials acting solely via adsorption (Shen et al., 2022). Laterite, though less studied, emerged as a promising low-cost option with high ammonium retention, particularly suitable for resource-limited rural settings (Tariq et al., 2023).

Compared with prior studies, conventional materials such as biochar, zeolite, and activated carbon remain relevant, yet their performance is surpassed in certain contexts by more targeted or combined solutions. This points to a shift in perspective: rather than seeking a "universal" material, selection should be guided by treatment objectives, substrate characteristics, and local availability. Table 1 synthesizes the main findings, enabling a comparative view of each material's strengths and limitations in terms of technical applicability, environmental performance, and cost.

Table 1. Comparison of support materials by removed nutrients, effect on biogas, cost, and applicability in anaerobic digestion.

Material	Nutrient removal	Nutriente removed	Biogas production	Relative cost	Reference
Biochar	High	NH_4^+, PO_4^3	15-30% increase	Low	Manga et al. (2023)
Zeolita	High	NH_4^+	5-10% increase	Low to medium	Fang et al. (2019)
Activated carbon	Moderate to high	NH_4^+, AGV	20-25% increase under inhibitory conditions	High	Hou et al. (2023)
Modified bentonite	High	NH_4^+, PO_4^{3-} (via struvite)	No negative impact reportes	Medium	Shen et al. (2022)
Perlite/Chitosan	Moderate	NH_4^+	23% increase	Low	Pilarska et al. (2025)
Laterite	High	NH_4^+	Not reported	Very low	Tariq et al. (2023)
Biochar/Zeolite/ Fe_3O_4	High	NH_4^+, PO_4^{3-}	35-40% increase	Medium	Zhang et al. (2023)

Practically, the results support flexible, context-specific strategies for digester design, where the support material is conceived not as passive packing but as an active lever for process optimization. Theoretically, the findings reinforce the need to integrate multidisciplinary approaches (environmental chemistry, microbiology, and life-cycle analysis) in the development of sustainable waste-treatment technologies.

Conclusions

The literature review showed that support materials with adsorptive capacity play a key role in optimizing anaerobic digestion—not only by stabilizing the process and improving biogas production, but also by facilitating the retention of nutrients such as nitrogen and phosphorus. Among the materials analyzed, biochar, zeolite, and their combinations with additives such as Fe_3O_4 exhibited the greatest technical and environmental potential, while alternatives such as modified bentonite, laterite, and hybrid systems like perlite/chitosan emerged as promising options for low-budget contexts. This study provides an integrated comparative analysis that can guide the selection of supports in anaerobic systems, particularly in regions such as Ecuador where sustainability and cost are critical factors. Further experimental research is recommended to validate the performance of these materials under local conditions and to assess their integration with nutrient-recovery technologies and subsequent circular applications.

References

Cuetos, M. J., Martinez, E. J., Moreno, R., Gonzalez, R., Otero, M., & Gomez, X. (2016). Enhancing anaerobic digestion of poultry blood using activated carbon. *Journal of Advanced Research*, *8*(3), 297–307. https://doi.org/10.1016/j.jare.2016.12.004

Fang, C., Huang, R., Dykstra, C. M., Jiang, R., Pavlostathis, S. G., & Tang, Y. (2019). Energy and Nutrient Recovery from Sewage Sludge and Manure via Anaerobic Digestion with Hydrothermal Pretreatment. *Environmental Science & Technology*, *54*(2), 1147–1156. https://doi.org/10.1021/acs.est.9b03269

Hou, Y., He, M., Liu, Y., Wang, Q., Yang, A., Yang, F., Lei, Z., Yi, X., & Huang, W. (2023). Biological nitrogen removal mechanisms during anaerobic digestion of swine manure: Effects of biogas circulation and activated carbon addition. *Bioresource Technology*, *374*, 128766. https://doi.org/10.1016/j.biortech.2023.128766

Manga, M., Aragón-Briceño, C., Boutikos, P., Semiyaga, S., Olabinjo, O., & Muoghalu, C. C. (2023). Biochar and Its Potential Application for the Improvement of the Anaerobic Digestion Process: A Critical Review. *Energies*, *16*(10), 4051. https://doi.org/10.3390/en16104051

Pilarska, A. A., Marzec-Grządziel, A., Makowska, M., Kolasa-Więcek, A., Jambulingam, R., Kałuża, T., & Pilarski, K. (2025). The Use of Chitosan/Perlite Material for Microbial Support in Anaerobic Digestion of Food Waste. *Materials*, *18*(15), 3504. https://doi.org/10.3390/ma18153504

Shen, Q., Yuan, J., Luo, X., Qin, Y., Hu, S., Liu, J., Hu, H., & Xu, D. (2022). Simultaneous Recovery of Nitrogen and Phosphorus from Sewage by Magnesium Ammonium Phosphate Method with Magnesium-Loaded Bentonite. *Langmuir*, *39*(1), 83–91. https://doi.org/10.1021/acs.langmuir.2c02043

Tariq, M., Mehmood, A., Abbas, Y., Rukh, S., Shah, F. A., Hassan, A., Gurmani, A. R., Ahmed, Z., & Yun, S. (2023). Digestate quality and biogas enhancement with laterite mineral and biochar: Performance and mechanism in anaerobic digestion. *Renewable Energy*, *220*, 119703. https://doi.org/10.1016/j.renene.2023.119703

Zhang, K., Deng, Y., Liu, Z., Feng, Y., Hu, C., & Wang, Z. (2023). Biochar Facilitated Direct Interspecies Electron Transfer in Anaerobic Digestion to Alleviate Antibiotics Inhibition and Enhance Methanogenesis: A Review. *International Journal of Environmental Research and Public Health*, *20*(3), 2296. https://doi.org/10.3390/ijerph20032296