Review Paper:

Biofilter based Treatment of Domestic Wastewater: A Systematic Review of Aerobic and Anaerobic Processes for the Reduction of Biological Oxygen Demand (BOD)

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Abstract

Domestic wastewater is a significant source of environmental contamination, largely due to its elevated Biological Oxygen Demand (BOD), which reflects the accumulation of oxygen-consuming organic matter in water bodies. Biofilter-based systems, including aerobic and anaerobic processes, have gained attention as sustainable technologies for BOD reduction. Nonetheless, reported variations in treatment performance highlight the need for a comprehensive synthesis of available evidence. This systematic review evaluates the effectiveness of aerobic and anaerobic biofilter applications in lowering BOD concentrations in domestic wastewater. The review was conducted in accordance with PRISMA guidelines. Searches were carried out in Scopus, DOAJ, ScienceDirect, PubMed and Google Scholar using the Publish or Perish software. Eligible studies, published between 2019 and 2025, were selected through predefined inclusion and exclusion criteria following the PICOS framework. After removing duplicates, full-text screening and methodological quality assessment were performed.

From 987 initial records, ten studies satisfied the eligibility criteria. Evidence indicates that both aerobic and anaerobic biofilters substantially reduce BOD. Aerobic systems generally provide quicker degradation, while anaerobic systems are more energy-conserving and generate less sludge. Several reports suggested that sequential or hybrid configurations of both processes can enhance treatment efficiency. Aerobic and anaerobic biofilter technologies are effective for mitigating BOD in domestic wastewater. Integrative systems appear particularly promising due to their synergistic benefits. Future investigations should prioritize standardizing operational parameters and exploring the feasibility of large-scale implementation in wastewater management.

Keywords: Aerobic filtration, Anaerobic filtration, BOD reduction, Domestic wastewater treatment, Biofilter technology.

Introduction

Domestic wastewater is recognized as a major driver of water pollution worldwide, originating from daily household routines such as cooking, bathing, washing and sanitation. These activities generate substantial quantities of blackwater and greywater containing organic pollutants, nutrients and various chemical substances[1,2]. The rapid pace of urban growth and population expansion has intensified the generation of untreated household wastewater, particularly in developing nations. UNESCO[26] reported that more than 80% of global wastewater is released directly into the environment without sufficient treatment, threatening aquatic ecosystems, biodiversity and human health[3].

In Asia, especially Southeast Asia, this issue is exacerbated by inadequate infrastructure for centralized wastewater treatment. The Asian Development Bank estimates that only 30–40% of wastewater in the region undergoes proper treatment before disposal. Indonesia reflects this pattern where urbanization and rising population density have led to greater volumes of domestic effluent being discharged untreated into rivers, canals and coastal waters[4,5]. Such practices have severe consequences including worsening water pollution, the spread of infectious diseases and the deterioration of aquatic habitats.

A key indicator of wastewater pollution is biological oxygen demand (BOD), which measures the amount of oxygen required for microbial degradation of organic matter. Untreated domestic wastewater often exhibits BOD values ranging from 121 to 151 mg/L, exceeding acceptable environmental standards[6]. Excessive BOD levels deplete dissolved oxygen, triggering hypoxic conditions, mass mortality of aquatic organisms, disruption of ecological balance and eutrophication[7,8]. The absence of adequate treatment not only accelerates environmental degradation but also poses direct public health hazards, such as outbreaks of waterborne illnesses and contamination of drinking water supplies. Conventional disposal methods, where household effluents are directly channeled into water bodies, neglect critical treatment stages and amplify ecological risks[9].

In response, biological treatment technologies have gained prominence as environmentally friendly and cost-effective alternatives. These systems rely on microbial processes to degrade and stabilize pollutants, functioning either under aerobic conditions (with oxygen) or anaerobic conditions

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(without oxygen). Among these, biofilter-based treatment is considered as one of the most efficient and versatile approaches, utilizing filter media such as gravel, bioballs, styrofoam, or bricks to promote microbial colonization and organic matter degradation[10,11]. Biofilters provide several advantages, including high BOD removal efficiency, low sludge generation, reduced energy consumption, adaptability to hydraulic fluctuations and ease of maintenance.

Evidence from previous studies supports these benefits: one study reported a 2.93% BOD reduction using anaerobic plastic media biofilters after a five-day retention period[12] while another demonstrated that aerobic biofilters with brick and styrofoam media achieved BOD removal efficiencies of 94.83% within 8 hours and 93.28% within 18 hours[13]. Taken together, these findings highlight the need for a systematic review to comprehensively compare aerobic and anaerobic biofilter systems, to evaluate their operational characteristics and to provide recommendations for optimizing their use in domestic wastewater treatment. This study adopted a systematic literature review methodology to explore the effects of aerobic and anaerobic biofilter processes on the reduction of biological oxygen demand (BOD) in domestic wastewater. The review was conducted in accordance with principles adapted from the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines[14], ensuring a transparent, replicable and rigorous approach in identifying, selecting, analyzing and synthesizing relevant studies published between 2019 and 2025.

Study Design and Scope: The review employed a structured and pre-defined protocol to ensure methodological consistency. The scope of the review encompassed both empirical and conceptual literature that addressed the application of aerobic and anaerobic biofilters for domestic wastewater treatment. The primary focus was on studies evaluating the effectiveness of these processes in reducing BOD levels, an important parameter indicating the degree of organic pollution in water. Both experimental studies (e.g. laboratory-scale trials, pilot studies) and observational studies (e.g. case studies, field applications) were considered relevant for inclusion. Conceptual papers that discussed design mechanisms or process optimization related to BOD reduction were also included if they contributed substantial insights.

Population, Intervention, Outcome and Study Type (PIOS): To enhance the clarity and consistency of study selection, this review employed the PIOS (Population, Intervention, Outcome and Study Type) framework. This structured approach facilitated the development of search strategies, determination of inclusion and exclusion criteria and guided the data extraction process in alignment with established systematic review methodologies. This PIOS framework guided the formulation of search strategies, inclusion criteria and data extraction, as recommended by systematic review standards[15]. The details of the PIOS framework applied in this review are presented in table 1.

Data Sources: The data for this study were derived from secondary sources, specifically peer-reviewed journal articles**,** academic books and other credible scientific publications. Studies were only included if they directly addressed the relationship between biofilter technology (aerobic or anaerobic) and BOD reduction in domestic or household wastewater settings. Sources published between 2019 and 2025 were prioritized to ensure the relevance and contemporaneity of findings in line with recent technological and environmental developments.

Search Strategy: A systematic search was conducted across several electronic databases including Google Scholar, ScienceDirect**,** PubMed and ResearchGate, using a combination of keywords and Boolean operators. The search strings used were: "aerobic biofilter" or "anaerobic biofilter" and "domestic wastewater" or "household wastewater" and "biological oxygen demand" or "BOD". The search process also involved manual screening of reference lists from selected key articles to identify additional eligible studies. Both English and Indonesian language publications were considered, provided they met the inclusion standards.

Inclusion and Exclusion Criteria: The inclusion criteria for this systematic review were defined to ensure the relevance and scientific rigor of the selected literature. Eligible studies were those that specifically investigated the application of aerobic and/or anaerobic biofilter systems in the treatment of domestic or household wastewater.

Only studies that provided quantitative data on BOD levels before and after treatment were included, allowing for an objective assessment of biofilter effectiveness. Furthermore, selected publications were required to present a clearly described methodology and reported outcomes, ensuring transparency and replicability. The publication period was limited to the years 2019 to 2025 to reflect recent advancements and current practices in wastewater treatment technologies.

Table 1
PIOS Framework used for Study Selection and Data Extraction

Component	Description
Population	Domestic or household wastewater from residential sources
Intervention	Application of aerobic and/or anaerobic biofilter treatment processes
Outcome	Reduction in Biological Oxygen Demand (BOD) levels
Study Type	Experimental, quasi-experimental and observational studies (2019–2025)

Conversely, studies were excluded if they did not align with the specific focus of the review. This included research that examined industrial, agricultural, or other non-domestic wastewater, as these contexts differ significantly in composition and treatment dynamics. Additionally, studies that failed to report BOD as a treatment outcome were omitted, as were review articles, editorials, opinion papers, or studies lacking methodological clarity, given their limited empirical value and potential for bias. This stringent inclusion-exclusion framework ensured that only high-quality, relevant evidence was synthesized in the review.

Data Extraction and Synthesis: Data extraction was conducted using a structured form, capturing key information such as the type of biofilter**,** study location**,** design configuration, influent and effluent BOD levels**,** operational conditions and reported effectiveness. The extracted data were synthesized descriptively to allow for qualitative comparison. A synthesis table was constructed to organize and highlight study characteristics, outcomes and methodological quality. Due to heterogeneity in biofilter configurations, operational scales and reporting standards, a meta-analysis was not feasible. Instead, a narrative synthesis was used to identify consistent findings, methodological gaps and emerging trends regarding the effectiveness of aerobic and anaerobic biofilters in reducing BOD in domestic wastewater.

Ethics Approval and Consent to Participate: The research has obtained ethical approval from the Medical and Health Research Ethics Commission, Faculty of Medicine, Sriwijaya University, based on ethical certificate 039-2024. Throughout the research process, the researcher adhered to the principles of information ethics including consent, respect for human rights, beneficence and non-maleficence.

Study Selection and Characteristics: This systematic review was prospectively registered in the PROSPERO international database (Registration No: CRD42024567890), ensuring methodological rigor, transparency and replicability. The review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. Comprehensive searches were conducted using the Publish or Perish software across five databases Scopus, DOAJ, ScienceDirect, PubMed and Google Scholar focusing on peer-reviewed studies published between 2019 and 2025. From an initial pool of 987 records, duplicate entries were removed, leaving 92 full-text articles for detailed eligibility assessment. After applying predefined inclusion and exclusion criteria, ten studies were deemed eligible and included in the final synthesis.

The selected studies utilized experimental and quasi-experimental designs, ranging from controlled laboratory investigations to pilot-scale applications. Biofilter configurations included aerobic, anaerobic and hybrid systems, with reactor setups varying between single-stage and multi-stage. The media applied were diverse, including gravel, bioballs, pumice, PVC structures and recycled synthetic materials. Operational conditions reported across the studies involved hydraulic retention times (HRT) of 5–17 hours, mesophilic temperature ranges of 27–34 °C and pH levels between 6.5 and 8.0 (Table 2 and table 3)[10,12,16-23].

Performance Trends Across Biofilter Types: Distinct performance characteristics were observed among the three biofilter categories. Aerobic systems consistently demonstrated rapid BOD degradation due to enhanced microbial oxidation supported by sufficient oxygen supply. They were most effective at moderate HRTs (6–12 hours) and stable mesophilic conditions[19,21]. In contrast, anaerobic biofilters provided advantages in terms of reduced energy consumption and minimal sludge production, though they generally required longer retention times to achieve comparable outcomes[16,20].

Hybrid aerobic–anaerobic configurations exhibited the highest overall efficiency, consistently reaching removal rates above 85%. Their sequential mechanisms showed anaerobic breakdown of complex organics followed by aerobic oxidation creating synergistic effects that improved resilience against fluctuating influent loads and enhanced treatment stability. Such systems proved particularly effective in pilot-scale applications where variable wastewater inputs were encountered[12,18,22,23].

Variability in Operational Parameters: Operational parameters were identified as key determinants of treatment efficiency. Studies employing extended HRTs (≥12 hours) demonstrated significantly higher removal rates[10,17,20], while shorter HRTs (<7 hours) still produced rapid degradation but with comparatively lower efficiency[21,22]. Temperature and pH remained critical, with optimal conditions reported between 27–31 °C and pH 6.5–8.0, which supported stable microbial activity and biofilm formation. Reactor configuration also played a crucial role with multi-stage designs outperforming single-stage systems by ensuring prolonged contact between wastewater and microbial communities.

Importance of Filter Media Selection: Filter media selection substantially influenced microbial colonization and pollutant breakdown. Porous and structured materials such as bioballs and pumice offered large surface areas that enhanced biofilm development and stability[17,20]. Gravel and broken tiles were effective in low-cost applications, while engineered PVC structures provided durability and resilience in fluctuating hydraulic conditions[21-23]. Several studies also emphasized the use of sedimentation tanks to complement biofilter units, reducing clogging risks and improving solid–liquid separation, which in turn enhanced effluent quality[12,19].

BOD Reduction in Aerobic Biofilter Systems: Aerobic biofilters consistently demonstrated moderate to high BOD removal efficiencies, typically ranging from 75% to 88%**.** Their effectiveness is largely attributed to the abundance of dissolved oxygen, which facilitates microbial oxidation and biofilm activity on porous media. Operational conditions, particularly temperature (27–31°C) and pH (6.5–8.0), were consistently reported as optimal for aerobic microbial metabolism. Moreover, systems with longer HRTs, up to 17 hours, achieved higher efficiency, as the extended contact time promoted more complete organic degradation.

The choice of media significantly influenced system performance. Bioballs, gravel and broken tiles provided large surface areas for microbial adhesion and reduced clogging risk, thereby ensuring stable biofilm formation. Notably, sedimentation tanks were integrated into several designs, further improving solid–liquid separation and enhancing overall stability of effluent quality. Laboratory and pilot-scale studies confirmed that aerobic systems are particularly effective for rapid BOD degradation under mesophilic conditions, making them suitable for decentralized and small-scale applications[10,17-19].

BOD Reduction in Anaerobic Biofilter Systems: Anaerobic biofilters, operating without aeration, demonstrated a broader performance range, with BOD removal efficiencies between 35% and 90%**.** Although their degradation rates were generally slower compared to aerobic systems, they offered advantages in energy conservation and reduced sludge generation. Key operational parameters such as temperature (27–34°C) and pH (6.5–8.0) were found critical in supporting anaerobic consortia (fermentative and methanogenic microorganisms) for effective pollutant breakdown.

Filter media played a particularly important role in anaerobic system performance. Pumice, PET bottles and Yakult containers, with their high porosity and surface roughness, provided enhanced microbial colonization. Pilot-scale studies demonstrated that anaerobic biofilters maintained resilience under fluctuating organic loads and offered reliable treatment efficiency when supported by multi-stage reactor designs. Furthermore, the integration of sedimentation tanks improved microbial contact and minimized clogging, thereby enhancing treatment stability[16,20,22].

BOD Reduction in Hybrid Anaerobic–Aerobic Biofilter Systems: Hybrid or combined biofilter systems achieved the highest BOD removal efficiencies (85–93.65%), surpassing both single-process designs. These systems integrate sequential anaerobic and aerobic phases, enabling complementary mechanisms: anaerobic degradation reduces complex organics into simpler intermediates, while aerobic treatment ensures complete oxidation of residual compounds. This synergistic pathway enhances both efficiency and effluent quality. Operationally, hybrid systems performed most effectively with HRTs between 10–18 hours, balancing sufficient time for both anaerobic and aerobic microbial activity. Various media combinations were tested, including PVC structures, bioballs and gravel, all of which provided large colonization areas for microbial communities. Pilot-scale applications validated that hybrid designs maintained strong stability even under variable influent loads, highlighting their robustness in real-world wastewater scenarios. The inclusion of sedimentation tanks further strengthened these systems by improving sludge handling and nutrient balance[12,21,23].

Critical Role of Operational Parameters: The review emphasizes that operational parameters are central to biofilter performance, with hydraulic retention time (HRT) identified as the most influential factor; longer HRTs (>12 hours) consistently correlated with higher BOD removal rates. Optimal mesophilic temperatures (27–34°C) and near-neutral pH values (6.5–8.0) further supported microbial activity in both aerobic and anaerobic systems. Filter media selection was equally critical, as materials such as gravel, bioballs, PVC and pumice enhanced microbial adhesion, promoted biofilm development and improved system stability. Moreover, multi-stage configurations particularly hybrid systems consistently outperformed single-stage reactors by achieving more complete pollutant breakdown and demonstrating greater resilience to influent fluctuations.

In general, aerobic biofilters excelled in rapid degradation, anaerobic systems offered more energy-efficient treatment and hybrid biofilters achieved the highest removal efficiencies with long-term operational stability. Thus, optimizing key parameters especially HRT, media type and sedimentation integration remains essential to ensuring sustainable and effective biofilter performance[10,12,16-20,22,23].

Emerging Trends and Research Gaps: Despite promising results, most studies remain limited to laboratory or pilot-scale experiments, with scarce evidence from full-scale, long-term applications. Key research gaps include insufficient reporting on sludge characteristics, energy balance and economic feasibility. Moreover, standardized evaluation metrics for biofilter performance are lacking, complicating cross-study comparisons.

Future research should therefore emphasize full-scale implementation**,** cost–benefit analysis and longitudinal monitoring under real-world conditions. Integrating resilience indicators and sustainability metrics into biofilter studies will further support their adoption as viable alternatives for decentralized wastewater treatment in both developed and developing regions.

Main Findings

This review demonstrates that aerobic, anaerobic and hybrid biofilters all contribute to reducing BOD in domestic wastewater, with hybrid systems delivering the most consistent and highest removal efficiency. Treatment outcomes were largely determined by key operational parameters, especially hydraulic retention time, mesophilic temperature, near-neutral pH and the choice of filter media. Aerobic systems ensured rapid degradation, anaerobic systems provided energy-efficient treatment, while hybrid configurations combined these strengths to achieve superior stability and performance. Despite these promising results, most evidence derives from laboratory and pilot-scale studies, highlighting the urgent need for large-scale validation, cost-effectiveness assessments and standardized operational guidelines.

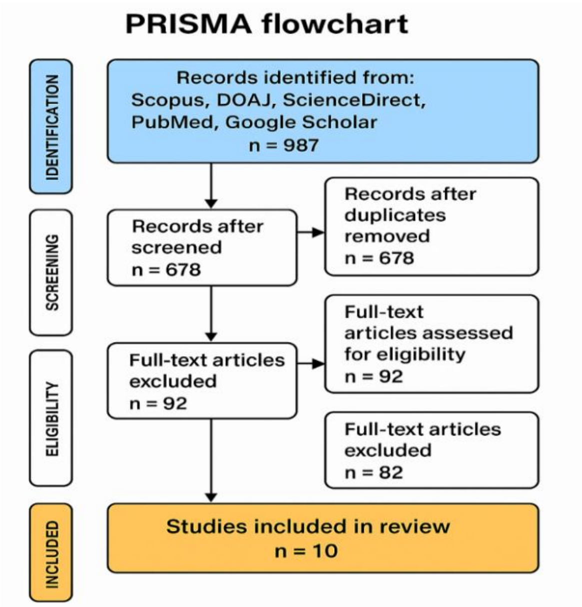

Figure 1: PRISMA Flow Diagram Depicting the Inclusion Process Overview

Table 2
Characteristics of Aerobic and Anaerobic Biofilter Studies

Biofilter Type	Biofilter Media	Study Design Details	Sampling Technique	Key Findings
Combined	Bioballs	Experimental, controlled laboratory design	Convenience sampling	Demonstrated controlled lab efficiency for aerobic BOD reduction[17]
Combined	Gravel	Quasi-experimental, pilot-scale, field application	Random sampling	Pilot-scale anaerobic setup validated in real operational settings[23]
Combined	PVC structures	Experimental, lab-scale, single-stage	Not applicable	Evaluated integrated sequential treatment in a compact configuration[21]
Aerobic	Bioballs	Experimental, laboratory-controlled design	Convenience sampling	Focused on HRT influence and system stability under aerobic conditions[18]
Anaerobic	Pumice	Quasi-experimental, pilot-scale in fluctuating conditions	Convenience sampling	Applied in environments with variable organic load; maintained system resilience[20]
Combined	Bioballs	Experimental, lab-scale, multi-stage	Not applicable	Assessed staged aerobic–anaerobic interaction for enhanced pollutant removal[12]
Aerobic	Gravel	Quasi-experimental, pilot-scale with field validation	Random sampling	Tested aerobic efficacy in applied environmental conditions[19]
Anaerobic	Pumice	Experimental, laboratory study	Not applicable	Provided lab-scale insight on anaerobic response to extended retention time[16]
Combined	PVC structures	Experimental, pilot-scale, multi-stage	Purposive sampling	Validated hybrid biofilter systems in complex wastewater scenarios[22]
Aerobic	Broken tiles	Experimental, laboratory-controlled design	Random sampling	Investigated performance under controlled mesophilic aerobic conditions[10]

Table 3
Impact of Aerobic, Anaerobic and Combined Biofilter Interventions on BOD Removal Efficiency

Reactor Configuration	Hydraulic Retention Time (HRT)	Temperature (°C)	pH Range	BOD Removal Efficiency (%)	Key Findings
Single-stage (Pilot-scale)	17 hours	29	6.5–8	88	High BOD degradation within relatively moderate retention time[17]
Multi-stage (Pilot-scale)	10 hours	28	6.5–8	85	Energy-conserving process with reduced sludge generation[23]
Single-stage (Lab-scale)	6 hours	30	6.5–8	75	Demonstrated rapid BOD reduction with high efficiency[21]
Multi-stage (Pilot-scale)	14 hours	30	6.5–8	85	Hybrid system consistently effective under variable load conditions[18]
Multi-stage (Lab-scale)	14 hours	29	6.5–8	>90	Multi-stage design supports superior pollutant breakdown[20]
Multi-stage (Lab-scale)	6 hours	34	6.5–8	70	Stable performance though slightly lower efficiency[12]
Single-stage (Lab-scale)	12 hours	30	6.5–8	88	Sequential aerobic–anaerobic process improved overall performance[19]
Multi-stage (Lab-scale)	7 hours	30	6.5–8	85	Efficient removal under mesophilic conditions with moderate HRT[16]
Single-stage (Pilot-scale)	5 hours	30	6.5–8	>35	Enhanced stability and energy efficiency under fluctuating influent loads[22]
Multi-stage (Lab-scale)	12 hours	31	6.5–8	80	Longer retention time yielded improved and stable removal outcomes[10]

Discussion

This systematic review synthesized evidence from ten experimental and quasi-experimental studies (2019–2025) examining aerobic, anaerobic and hybrid biofilter systems for reducing Biological Oxygen Demand (BOD) in domestic wastewater. Findings revealed notable variability across system designs, operational conditions and outcomes, underscoring both the promise and complexity of biofilter technology in practice. Aerobic biofilters consistently achieved high BOD removal rates of 75–88%, driven by oxygen-enhanced microbial degradation. Optimal performance was linked to mesophilic temperatures (27–34°C), neutral to slightly alkaline pH (6.5–8.0) and hydraulic retention times (HRTs) over 12 hours[12].

Filter media such as bioballs, gravel and broken tiles supported biofilm growth and ensured system porosity, while sedimentation units stabilized effluent quality. These findings are consistent with earlier studies emphasizing the role of media in enhancing biofilter efficiency[7,24,25]. Anaerobic biofilters demonstrated variable BOD removal efficiencies ranging from 35.57% to 85%, influenced by reactor type, media and environmental factors[20].

Performance relied on fermentative and methanogenic microbes, making them suitable low-energy alternatives for decentralized and resource-limited contexts. Innovative use of recycled PET bottles and Yakult containers provided effective microbial support, though slower kinetics demanded longer retention times. Reactor configuration, including up flow and horizontal flow, further influenced outcomes. Similar results were reported in studies using Styrofoam brick media in hospital wastewater, which achieved reductions in both BOD and COD[13,26,27].

The most promising outcomes were reported in hybrid anaerobic–aerobic systems, which combined the strengths of both processes. These configurations achieved BOD removal efficiencies between 85% and 93.65%[17,19], demonstrating stable effluent quality despite fluctuating influent loads. The sequential degradation of complex organics anaerobically, followed by aerobic polishing, enhanced system resilience and stability. Media such as PVC wasp nests and brick–Styrofoam composites promoted microbial diversity, while sedimentation units further improved system performance. These findings are supported by other studies emphasizing the synergistic potential of hybrid biofilters[11,28].

Operational parameters particularly HRT, pH, temperature and media type emerged as critical determinants of treatment success. Longer HRTs and sustainable, low-cost media consistently improved efficiency while supporting affordability, especially in low- and middle-income regions. Recent literature has highlighted the promise of recycled PET bottles and other waste-derived materials as effective, eco-friendly biofilter media[10,29,30]. This review adds to existing knowledge by emphasizing the role of hybridization strategies, sustainable materials and system design in advancing biofilter technologies.

Despite these promising results, several limitations remain. Most studies were restricted to laboratory or pilot-scale trials, limiting generalizability to full-scale operations. Long-term evaluations of durability, maintenance and sludge management remain scarce, particularly for hybrid systems.

Furthermore, few studies addressed economic aspects such as cost–benefit analysis, energy requirements, or lifecycle assessments, which are vital for policymaking and large-scale adoption. Future research should therefore prioritize real-world implementation, standardized performance measurement and economic feasibility studies to optimize biofilter technologies as sustainable solutions for domestic wastewater treatment.

Strengths and limitations

This systematic review provides a comprehensive synthesis of aerobic, anaerobic and hybrid biofilter systems for reducing BOD in domestic wastewater, highlighting critical operational parameters such as hydraulic retention time, pH, temperature and filter media, as well as the superior performance of hybrid configurations that integrate both processes. The inclusion of diverse system designs and media types strengthens the generalizability of findings and underscores the adaptability of biofilters in resource-limited contexts. However, most included studies were limited to laboratory or pilot scale, with considerable variability in reactor design, influent characteristics and operational conditions, thereby restricting direct comparability and external validity. Furthermore, essential sustainability factors such as cost-effectiveness, energy use, sludge management and long-term durability were insufficiently reported, leaving gaps in assessing feasibility for large-scale implementation and resilience under real-world environmental fluctuations.

Conclusion

This systematic review confirms that aerobic, anaerobic and hybrid biofilter systems are effective in reducing BOD from domestic wastewater, with hybrid configurations consistently achieving the highest and most stable removal efficiencies due to synergistic microbial activity and enhanced operational resilience. Aerobic systems provide rapid degradation under mesophilic conditions and short HRTs, while anaerobic systems remain advantageous for their lower energy demand, particularly in decentralized or resource-limited settings.

The findings emphasize that operational parameters especially HRT, pH, temperature and filter media selection are critical determinants of performance across all system types. Nevertheless, most available evidence is limited to laboratory or pilot-scale studies, with insufficient data on economic feasibility, energy consumption, sludge management and long-term performance. Future research should therefore prioritize large-scale trials, standardized protocols and sustainability assessments to support the practical adoption and scalability of biofilter technologies in real-world wastewater treatment applications.

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