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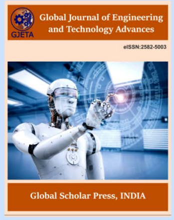

(REVIEW ARTICLE)

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A review on the application of biochar in anaerobic biofiltration for wastewater purification: technologies, performance, and future perspectives

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Abstract

Water pollution, driven largely by industrial activities, presents a pressing environmental challenge, compromising ecosystems and human health globally. Conventional wastewater treatment methods, such as adsorption and membrane filtration, while effective, are often limited by high costs and inefficiencies in handling complex effluents, particularly in resource-limited settings. This review explores the integration of biochar a porous, carbon-rich material derived from biomass pyrolysis into anaerobic biofiltration systems as a sustainable solution for wastewater purification. Focusing on literature predominantly from the past decade, biochar's unique properties was examined, including its high surface area (10–500 m^2/g), porosity (0.1–0.5 cm^3/g), and oxygen-containing functional groups, which enable it to serve as an effective adsorbent, biofilm carrier, and electron transfer mediator. Empirical studies demonstrate that biochar-amended anaerobic biofilters significantly enhance treatment performance, achieving, up to 74% chemical oxygen demand (COD) removal and improved pathogen reduction (1.35 log-units of *E. coli*) compared to traditional systems. These improvements stem from biochar's ability to boost microbial activity and pollutant sequestration. However, challenges such as variability in biochar properties, scalability, and the lack of long-term performance data impede widespread adoption. This review highlights key research gaps and proposes future directions, including standardizing biochar production and conducting extended field studies, to optimize its application in anaerobic biofiltration technologies for efficient and cost-effective wastewater treatment.

Keywords: Biochar; Anaerobic biofiltration; Wastewater treatment; Direct interspecies electron transfer (DIET); Circular economy

1. Introduction

Water pollution is one of the most formidable environmental challenges confronting humanity today, rivalling climate change in its scope and urgency [1]. Industrial activities are the primary source of water pollution, as the increasing release of contaminants into water bodies has severely compromised ecological integrity and human health on a global scale [2]. Some of the pollutants include nitrates, phosphorus, heavy metals (cadmium, arsenic, mercury, lead, and chromium), synthetic dyes, cyanides, biomedical waste, petroleum derivatives, oil spills, and agricultural residues. The consequences of these pollutants are significant, leading to biodiversity loss and habitat degradation in aquatic ecosystems, while human populations experience increased risks of waterborne diseases such as cholera and typhoid, along with chronic conditions like genetic disorders, infant mortality, and respiratory ailments [3]. Moreover, prolonged exposure to specific contaminants such as lead and cadmium has been linked to severe health outcomes, including kidney and liver malfunctioning, cancer, neurological impairments, memory loss, aggression in children, and pregnancy complications. In developing nations, the crisis is particularly acute. Thus, there must be a critical need for innovative, sustainable, and cost-effective wastewater treatment solutions.

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Conventional wastewater treatment technologies including ion exchange, adsorption, membrane filtration, reverse osmosis, flotation, coagulation-flocculation, precipitation, solvent extraction, and electrochemical methods have long been deployed to mitigate water pollution [4]. While these methods can be effective to varying degrees, they are often beset by significant limitations. High operational costs, challenges in reuse and recycling, and difficulties in treating the complex, heterogeneous nature of industrial effluents restrict their applicability, particularly in resource-constrained settings [5]. Among these, adsorption has been the preferred technique in developing and under-developed regions due to its operational simplicity and robust pollutant removal efficiency [6]. Traditional adsorbents such as silica gel, activated carbon, fuller earth, molecular sieves, zeolites, and ion-exchange resins have been widely utilized to sequester organic and inorganic contaminants [7]. However, the environmental footprint and cost of these materials have prompted a shift toward sustainable alternatives, with biomass-derived biochar proving as a compelling alternative which is evident with the increased number of research over the last decade (Fig. 1).

Biochar is a carbon-rich, porous material produced through the thermal decomposition (pyrolysis) of agricultural residues or forestry biomass under oxygen-limited conditions at temperatures ranging from 300 to 1000°C [8]. Its physicochemical properties, high surface area (10–500 m^2/g), substantial carbon content (50–90%), porosity (0.1 to 0.5 cm^3/g), and a rich array of oxygen-containing functional groups (e.g., hydroxyl, carboxyl) make it an exceptionally effective adsorbent for a broad spectrum of pollutants. Nevertheless, biochar's performance is not without caveats. Its efficacy varies significantly depending on feedstock type, pyrolysis conditions, and target contaminants, leading to inconsistent outcomes across applications. Post-treatments such as chemical activation can enhance its adsorption capacity, but these processes increase complexity and costs, potentially eroding biochar's economic advantage over conventional adsorbents. Additionally, challenges related to regeneration and reusability often result in diminished performance over successive cycles, necessitating further research to optimize its practical utility.

Concurrently, anaerobic biofiltration a biological wastewater treatment process wherein microorganisms degrade organic matter in the absence of oxygen offers a sustainable complement to adsorption-based approaches. This technique is distinguished by its low energy requirements and the generation of biogas, a renewable energy byproduct that enhances its environmental appeal. When integrated with biochar, anaerobic biofiltration systems capitalize on biochar's dual role as an adsorbent and a supportive matrix for microbial colonization, thereby amplifying treatment efficiency [9]. Recent empirical studies highlight the promise of this synergy [10, 11, 12]. For example, in one of the studies, Miscanthus-derived biochar in anaerobic biofilters achieved 74 ± 18% COD removal compared to 61 ± 12% for sand filters, alongside improved E. coli reduction (1.35 ± 0.27 log-units vs. 1.18 ± 0.31 log-units) [10]. These findings affirm biochar's capacity to augment pollutant removal and microbial activity in anaerobic biofiltration systems.

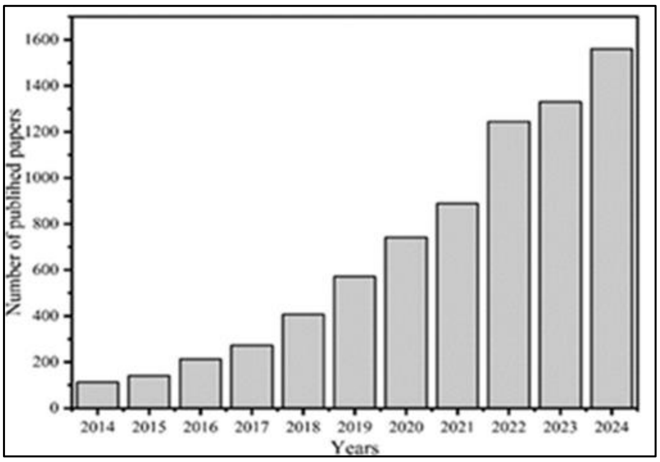

Figure 1 Number of biochar-related publications for water treatment from 2014 to 2024 [15]

Despite these advances, limited studies [10] have been conducted on long-term performance data for biochar-enhanced anaerobic biofiltration systems, obscuring their durability and reliability in real-world settings. Although, there is a wealth of research on biochar physicochemical properties and its use in various wastewater treatment processes, a notable gap persists regarding its integration into anaerobic biofiltration systems. Most studies have focused on isolated aspects of biochar performance or short-term, laboratory-scale applications, leaving critical issues such as long-term sustainability, and the synergistic association between biochar characteristics and anaerobic microbial processes largely unaddressed. Moreover, a lack of standardized protocols for tailoring biochar properties such as surface area, porosity, and functional group composition to specific pollutants hinders optimization efforts [13]. Scalability poses another challenge, as most studies have been confined to laboratory or pilot scales, with little insight into the feasibility of large-scale deployment in anaerobic biofiltration [14].

Hence, this review seeks to comprehensively study the application of biochar in anaerobic biofiltration for wastewater purification. It will elucidate the properties of biochar, conventional technologies of anaerobic biofiltration, and how biochar has been applied in anaerobic biofiltration. Additionally, it will delineate future research directions to address current limitations, including optimization of biochar properties for anaerobic biofiltration, and long-term sustainability evaluations. The uniqueness of this paper lies in its focus on studies published in the last 10 years, with limited exceptions, offering a recent perspective compared to existing literature.

2. Biochar properties

The properties of biochar are influenced by feedstock composition (e.g., lignocellulosic vs. manure-based) and pyrolysis parameters such as temperature, heating rate, and residence time. At higher pyrolysis temperatures (above 500°C), biochar typically exhibits a more aromatic carbon structure, a higher fixed carbon content, and reduced amounts of labile functional groups [16]. In contrast, lower-temperature biochar (300–400°C) retains more oxygenated functional groups like carboxyl (-COOH), hydroxyl (-OH), and carbonyl (-C=O), which are crucial for the adsorption of polar and ionic contaminants [17].

One of the most significant characteristics of biochar is its specific surface area (SSA), which can range from a few m^2/g in low-temperature biochars to over 2000 m^2/g in activated variants [18]. The formation of micropores (<2 nm) and mesopores (2–50 nm) is influenced by both feedstock composition (e.g., lignin content) and activation methods (chemical or physical). This porous network underpins the adsorption capacity for heavy metals, dyes, and organic pollutants and influences microbial colonization in environmental applications [19].

Another significant property of biochar is its pH which typically ranges from neutral to alkaline, especially for biochars produced above 500°C, where inorganic ash content increases [20], this alkalinity can help neutralize acidic soils and buffer pH in aquatic systems. Electrical conductivity (EC) on the other hand tends to rise with increasing temperature, associated with the release and concentration of mineral ions. Additionally, the cation exchange capacity (CEC) is closely linked to the presence of negatively charged functional groups on the biochar surface; hence, moderate-temperature biochars can exhibit higher CEC due to partially retained polar sites [21].

2.1. Factors influencing biochar properties and performance

The subsequent sections will provide a review of how pyrolysis temperature and feedstock, surface functional groups, competing ions and ionic strength, and pH determine biochar's properties and performance.

2.1.1. Effect of pyrolysis temperature and feedstock

Pyrolysis temperature is widely recognized as a decisive factor in determining the physicochemical properties, yield, and ultimate performance of biochar. Studies [8] have demonstrated that increasing pyrolysis temperature, typically within the range of 300-1000 °C, triggers a series of structural and compositional changes that profoundly impact biochar's efficacy for soil amendment, pollutant adsorption, and carbon sequestration. Zhang et.al [22] studied four feedstocks wheat straw, corn straw, rape straw, and rice straw pyrolyzed at 300, 400, 500, and 600 °C for 1 h, it was found that biochar yields declined steadily as the temperature rose, particularly beyond 400 °C. Rice straw-derived biochar maintained a comparatively higher yield due to its elevated ash content. Alongside yield reduction, key properties such as hydrogen, oxygen, H/C, O/C, and (O+N)/C ratios all decreased with temperature, whereas carbon content, ash, pH, electrical conductivity, and surface roughness increased. This trend indicates that higher temperatures promote the formation of more carbonized, recalcitrant structures that can be suitable for material applications, albeit at the expense of certain functional groups.

In another research carried conducted by Li et.al [23], the effect of pyrolysis temperature (175-950 °C) and feedstock type (corn stover, switchgrass, and wood) was quantified across thirty-six compositional characteristics of biochar. Results showed that feedstock type often exerted a stronger influence on properties than temperature alone, although rising pyrolysis temperatures consistently led to an increase in total carbon up to 10.14% higher in some cases and an improvement in cation exchange capacity (CEC). Dissolved organic carbon, conversely, was reduced exponentially at higher temperatures, while polarity indices also shifted accordingly. Therefore, aside from the increase in temperature, the feedstock's intrinsic composition (e.g., lignin and cellulose content) interacts with the chosen pyrolysis temperature to yield biochars with distinct functionalities.

Furthermore, a separate study focused on biochars produced from beech woodchips, walnut shells, and wheat-rye straw, pyrolyzed at 400, 500, 600, and 700 °C. The yields decreased as temperatures increased, and also carbon content, while hydrogen content declined, reflecting the progressive carbonization of the material. Higher pyrolysis temperatures also yielded higher pH and total organic carbon (TOC) values. Ash content behaviour varied depending on the feedstock, highlighting that the impact of temperature is modulated by precursor composition. The Brunauer-Emmett-Teller (BET)-specific surface area generally trended upward with temperature, except for some cases (e.g., straw-based biochars) where excessive heating collapsed pores. The Fourier-transform infrared (FTIR) analyses revealed a reduction in functional group diversity and density at elevated temperatures, though certain feedstocks (like beech woodchips) exhibited intense C–O stretching vibrations at 600–700 °C. This trait could compensate for lower surface area by offering active sites conducive to adsorption processes [24].

Another key observation from the work of Qiu et al. [15] is that increasing pyrolysis temperature transforms amorphous carbon into a more graphite-like microcrystalline structure, leading to a more stable product suitable for carbon sequestration. For instance, biochar derived from corn straw and pyrolyzed at 500 °C might exhibit a balance of surface functional groups and sufficient surface area, whereas pyrolysis at 700 °C or above can result in pore collapse and reduced functional group density, diminishing adsorption capacity [25]. This particular study done by Qiu et. al. [25] quantified such shifts: Cd^{2+} removal capacity was shown to peak at 45 mg/g at 500 °C but declined to 30 mg/g at 700 °C. Similarly, $ZnCl_2$-modified biochar exhibited maximum methylene blue removal at 600 °C, dropping beyond that temperature threshold. In the case of rice straw biochar, the specific surface area increased from 10 m^2/g at 300 °C to 250 m^2/g at 600 °C, eventually plateauing or dropping if temperatures exceeded 800 °C.

2.1.2. Effect of surface functional group

Surface functional groups significantly influence biochar's behaviour in environmental applications, particularly soil amendment and water retention. Research [26] has shown that biochars produced at lower temperatures (e.g., 350 °C) or subsequently oxidized at mild conditions (e.g., 250 °C) exhibit higher densities of oxygenated functional groups (carboxylic, hydroxyl, and carbonyl). These groups enhance hydrophilicity, wettability, and interaction with soil matrices. For instance, oxidized biochar derived from pine bark or poplar wood displayed better water retention in sandy soils, indicating strong correlations between acidic functional groups and soil moisture content across a wide range of matric potentials [26].

Meanwhile, two-dimensional (2D) ^{13}C NMR studies [27] have revealed that biochar functional groups evolve through dehydroxylation, dehydrogenation, and aromatization processes. O-alkylated carbons are cleaved at moderate temperatures, whereas higher temperatures promote fused-ring aromatic structures. Consequently, the presence and density of these functional groups directly impact pH, electrical conductivity, and the adsorptive capacity of biochar. Low-temperature or oxidized biochars tend to retain more labile functional groups, boosting their efficacy in soil conditioning and pollutant remediation [27].

2.1.3. Effect of competing ions and ionic strength

Competing ions and ionic strength significantly influence the adsorption capacity and selectivity of biochar for various pollutants, including dyes and heavy metals. Research [28] shows that high salt concentrations or the presence of other cations in solution can either enhance or inhibit adsorption, depending on the charge interactions and the specific ionic environment. For instance, glucose-based biochars modified with NaOH exhibited superior adsorption for methylene blue (MB), but adding KCl further increased MB uptake by encouraging dimerization of dye molecules and intensifying electrostatic attractions. Meanwhile, cellulose-based biochars showed a different trend: when ionic strength rose beyond a certain threshold, the adsorption efficiency declined due to electrostatic shielding and competition between K^+ ions and MB molecules for active sites. Surfactants such as CTAB also modulated adsorption, either boosting it through hydrophobic interactions or reducing it when the surfactant and dye charges conflicted. Furthermore, an acidic salt like $NaHCO_3$ often improves adsorption by altering pH conditions, thereby enhancing dye-surface interactions [28]. In heavy metal removal studies [29], rapeseed cake biochar demonstrated high Cu(II) adsorption capacities in single-metal solutions; however, elevated arsenic(III) concentrations in the same system reduced its efficiency for Cu(II) and Zn(II). This was attributed to the competitive binding of arsenic(III) or the alteration of electrochemical conditions, both of which can block or alter the biochar's active adsorption sites. Hence, it is important to evaluate wastewater conditions, where multiple ions, pH fluctuations, and ionic strengths coexist.

2.1.4. Effect of pH

pH exerts a profound influence on how biochar performs in both aqueous and soil environments, often dictating pollutant transformations and metal speciation. In water treatment contexts, highly alkaline porous (HAP) biochar (pH

≈ 9.2) made from corn stover can raise the pH of deionized water (initially pH 5.4) by nearly one unit, whereas red oak biochar (pH ≈ 7.5) exerts a more moderate effect. For tap water at pH 9.5, HAP biochar tends to maintain or slightly increase the already alkaline conditions, while red oak biochar can shift it downward due to differences in functional group density and buffer capacity. This pH manipulation near the water-air interface can mitigate gaseous emissions by controlling the local chemical environment [30].

3. Application of biochar in wastewater treatment technologies: The role of its unique properties

Wastewater treatment is foundational to environmental sustainability, it is designed to protect public health and safeguard ecosystems by removing contaminants from water before its discharge or reuse. The complex nature of wastewater, containing a diverse array of pollutants from suspended solids and organic compounds to pathogens and dissolved nutrients necessitates a multi-stage treatment process. These stages are typically classified into physical, chemical, biological, and advanced tertiary treatments, each contributing uniquely to pollutant removal [32]. The integration of these processes is critical, as each stage not only alleviates the load for subsequent treatments but also enhances overall treatment efficiency, thereby ensuring that effluent quality meets stringent regulatory standards.

Biochar's distinctive characteristics such as a high specific surface area, porosity, and an abundance of oxygen-containing functional groups make it a versatile material for enhancing various stages of wastewater treatment. These properties enable biochar to interact effectively with contaminants and support biological processes, thereby improving overall treatment efficiency.

In physical and preliminary treatment processes, biochar's hierarchical porous structure can complement traditional screening and sedimentation methods. Its ability to adsorb fine particulates helps reduce the load of suspended solids and organic matter, thereby easing the burden on downstream treatment stages [33].

During chemical treatment, biochar's surface functional groups (e.g., hydroxyl, carboxyl) play a crucial role in adsorbing dissolved pollutants and facilitating coagulation-flocculation processes [34]. By interacting with chemical coagulants, biochar enhances the aggregation of colloidal particles and accelerates their removal through sedimentation and subsequent chemical precipitation [9].

In biological treatment systems, biochar serves as a good support medium for microbial colonization [35]. Its high surface area and bioactive sites encourage the formation of biofilms, which are essential for processes such as the activated sludge system, trickling filters, and moving bed biofilm reactors [36] This microbial attachment not only accelerates the degradation of organic pollutants but also improves the stability and resilience of the microbial community, leading to enhanced contaminant breakdown and energy recovery via biogas production.

Furthermore, the surface chemistry and adsorption capacity of biochar can enhance advanced tertiary treatment processes by effectively removing trace contaminants and facilitating catalytic reactions. It can capture trace organic contaminants that may elude conventional methods like membrane filtration or activated carbon adsorption. In addition, when integrated with ion exchange processes or advanced oxidation processes (AOPs), biochar aids in transforming persistent pollutants into more biodegradable forms, ensuring that the treated effluent meets high-quality discharge or reuse standards [37].

However, among these diverse treatment strategies, anaerobic biofiltration has gained attention over the last decade as a promising technology as shown in Fig. 2. It is classified under anaerobic biological treatment, anaerobic biofiltration leverages the natural capabilities of microorganisms that form biofilms on porous media, operating in oxygen-deprived environments. This process is uniquely capable of handling high-strength organic wastes while concurrently producing biogas a valuable energy byproduct. The integration of biofiltration with anaerobic digestion not only enhances contaminant degradation but also offers a sustainable, energy-efficient alternative to conventional processes. A summary of different works that have studied the effect of biochar performance in wastewater treatment as a function of its properties is presented in Table 1.

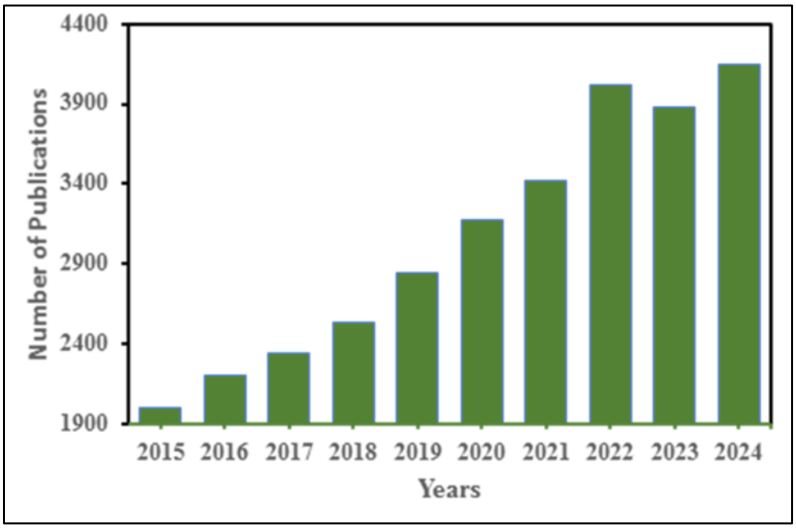

Figure 2 Number of Biofiltration-related publications from 2015 to 2025

Table 1 Summary of factors influencing biochar properties and performance in wastewater treatment applications

Factor	Key Findings	Inferences	References
Pyrolysis Temperature and Feedstock	Increasing temperature (300–1000 °C) generally decreases biochar yield while enhancing carbonization, pH, ash content, electrical conductivity, and BET-specific surface area.	Higher temperatures yield more recalcitrant, carbonized biochars suitable for material applications but may compromise adsorption capacity due to reduced functional groups.	[23, 24, 25, 31]
	Ratios such as H/C, O/C, and (O+N)/C decline with higher temperatures.	Selecting the appropriate feedstock is critical to achieving desired biochar functionalities.	
	Feedstock intrinsic composition (e.g., lignin and cellulose content) strongly influences these trends; for instance, rice straw may yield higher biochar due to elevated ash content.		
Surface Functional Groups	Biochars produced at lower temperatures or subjected to mild oxidation retain higher densities of oxygenated groups (carboxyl, hydroxyl, carbonyl), which enhance hydrophilicity and interactions with pollutants.	The presence and density of functional groups directly affect biochar's water retention, pH regulation, and adsorptive capacity key for both soil amendment and pollutant remediation.	[26, 27]
	Elevated temperatures lead to dehydroxylation, dehydrogenation, and aromatization, reducing functional group diversity.		
Competing Ions and Ionic Strength	High salt concentrations or the presence of competing cations (e.g., K^+, Na^+) can either enhance or inhibit adsorption efficiency.	The ionic environment is a critical factor in real wastewater conditions, influencing the binding efficiency of biochar; optimization must consider competitive interactions among ions.	[28, 29]
	In dye adsorption, certain salts may promote interactions via electrostatic effects, whereas, in heavy metal removal, competitive binding can reduce capacity.		

pH	Biochar can significantly alter the pH of aqueous environments depending on its inherent pH (e.g., highly alkaline biochars can raise solution pH, while others may lower it)	Manipulating pH through biochar application is vital for optimizing its adsorptive performance and controlling pollutant transformations and gaseous emissions.	[30]
	pH affects pollutant speciation and adsorption dynamics.		

4. Anaerobic biofiltration technologies

Anaerobic biofiltration technologies are advanced wastewater treatment systems that combine biological degradation with filtration mechanisms to efficiently remove pollutants, recover resources, and generate bioenergy under oxygen-free conditions [38]. These systems leverage microbial consortia and specialized reactor configurations to degrade organic matter, neutralize toxic compounds, and recover valuable byproducts such as methane, hydrogen, and metals [39]. Their adaptability to diverse wastewater types from high-strength industrial effluents to complex organic streams makes them critical for sustainable water management and circular economy goals [22].

Building on these fundamentals, a variety of reactor configurations have been developed to optimize these processes under specific operational conditions. Designs such as the up-flow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB), anaerobic fixed-bed reactor (AFBR), and anaerobic sequencing batch reactor (ASBR) exemplify tailored approaches that enhance biomass retention, pollutant degradation, and resource recovery. Fine-tuning parameters like hydraulic retention time, influent composition, and pre-treatment steps, these systems have demonstrated significant improvements in heavy metal remediation, organic degradation, and bioenergy production. The following sections provide an in-depth exploration of each reactor type, highlighting recent experimental findings and technological advancements that showcase their performance and versatility in treating diverse wastewater streams.

4.1. Upflow Anaerobic Sludge Blanket (UASB) reactor

The up-flow anaerobic sludge blanket (UASB) reactor is widely recognized for its capacity to treat various types of wastewater under anaerobic conditions, achieving both pollutant removal and resource recovery. In recent studies, UASB reactors can stably produce hydrogen, remove heavy metals, and degrade complex organics, depending on operating conditions such as hydraulic retention time (HRT), influent composition, and pretreatment steps. One experiment examining starchy wastewater supplemented with groundnut de-oiled cake reported a maximum hydrogen production rate of 12.3 L L^{-1} d^{-1} at 3 h HRT, highlighting the reactor's effectiveness once a sufficient sludge height was established [40]. In another study [41] focusing on lead remediation, the UASB reactor achieved Pb(II) removal efficiencies between 90 and 100% for inlet concentrations ranging from 80 to 2000 ppm, with a maximum removal rate of 1948.4 mg/(L d). XRD and XPS analyses of the resulting precipitate confirmed the presence of Pb^0, PbO, PbS, and $PbSO_4$, this highlights the reactor's potential for metal recovery. Additionally, textile wastewater treatment using a UASB system has shown that pre-treatment steps and reactor variables such as influent chemical oxygen demand (COD) and HRT significantly influence removal efficiency. Statistical models (R^2 = 0.99) revealed that COD removal could reach 70% without pretreatment and 95% with a composite coagulant (MC + ACH), while colour removal improved from 81% to 100% when pre-treatment was applied [42].

4.2. Expanded Granular Sludge Bed (EGSB) reactor

The Expanded Granular Sludge Bed (EGSB) reactor is an advanced variant of upflow anaerobic systems, designed to enhance granular sludge stability and increase hydraulic efficiency. Recent studies show that adding specific materials, such as magnetite nanoparticles (Fe_3O_4NPs) or hydroxyapatite particles (HAPs), can significantly improve biomass retention and microbial performance in EGSB configurations. For instance, one experiment [43] reported that adding 50 mg/L of Fe_3O_4NPs at 40–60 nm increased hydrogen production to 4.95 L H_2/d in an EGSB reactor, while simultaneously shifting fermentation pathways from butyrate-type to ethanol-type.

Another study [44] demonstrated that HAPs, used as a granulation activator, aided in forming denser biomass aggregates with enhanced ability to settle, increasing nitrogen removal from 2.8 to 13.7 gN/L/d over 193 days. This accelerated the adaptation and start-up processes, resulting in improved bio-activity (0.52 gN/gVSS/d) and structural stability of the sludge. Additionally, pilot-scale work on a 7 m tall EGSB reactor with an up-flow velocity of 1.75 m/h and a 4 h HRT indicated a pH rise from 5.1 to 8.2 and COD reduction of 41.1% within four days, demonstrating that seeding with granulated anaerobic bacteria expedited reactor start-up.

4.3. Anaerobic Fixed-Bed Reactor (AFBR) / Submerged Anaerobic Biofilter

Anaerobic fixed-bed reactors (AFBRs), sometimes referred to as submerged anaerobic biofilters, have gained attention for treating high-strength industrial wastewater with considerable organic loads. Recent studies have demonstrated that introducing immobilized media and trace elements can significantly enhance COD removal and biogas production. In one study treating natural rubber wastewater, the addition of Fe(II) and immobilization media yielded over 90% COD removal, with improved methane production rates under both batch and semicontinuous modes. Kinetic modelling (e.g., Stover–Kincannon) confirmed high reaction rate constants, indicating strong biofilm development on the fixed media [45].

In another study [46] focusing on cassava starch wastewater, an AFBR with biofilters shaped like honeycomb “bee nest” modules achieved 98% COD removal and 4.8 L/L·day biogas production at an organic loading rate (OLR) of 1.72 g/L·day and a 6-day hydraulic retention time (HRT). The reactor’s performance proved robust even under variable pH (4.5–7) and moderate temperature conditions (29–30 °C). The presence of immobilized biomass on the fixed bed allowed for stable degradation of high organic loads, suggesting that microbial consortia effectively adapted to the system.

A separate trial dealing with palm oil mill effluent (POME) reported total suspended solids (TSS) removal of 68–89% and low sludge volume indices (SVI) between 11 and 35 L/mg. By reducing the HRT stepwise from 24 to 4 hours, the volumetric loading rate increased from 4.0 to 13.8 kg COD/m^3·d without significant operational difficulties. This result highlights the AFBR’s resilience and superior performance in handling wastewater streams containing substantial suspended solids [47].

4.4. Anaerobic Sequencing Batch Reactor (ASBR)

Anaerobic sequencing batch reactors (ASBRs) have shown significant potential for treating various high-strength wastewaters while enhancing bioenergy production. Their efficiency largely depends on microbial community dynamics and process conditions. In one study on phenol degradation, an ASBR was operated with increasing phenol concentrations from 120 to 1200 mg/L. Microbial community analysis using 16S rRNA sequencing identified dominant taxa, including Anaerolineae, Bacteroidia, Clostridia, and Methanobacteria. The bamA gene, associated with anaerobic aromatic degraders, showed a strong correlation with phenol degradation rates. At an optimal phenol concentration of 800 mg/L, the highest relative abundances of Syntrophorhabdus, Chloroflexus, Smithella, Methanolinea, and Methanosaeta were observed, indicating their role in maintaining reactor performance. A shift in methanogenic populations was noted, where hydrogenotrophic Methanobacterium declined, while Methanobrevibacter increased, highlighting the impact of phenol on archaeal dynamics [48].

Furthermore, a novel three-stage ASBR system was developed by Jiraprasertwong et al. [49] for methane production from ethanol wastewater, operating at 37°C with a fixed 1:1 effluent-to-feed recycle ratio. The first bioreactor was maintained at pH 5.5, while the second and third reactors operated without pH control. Under an optimal chemical oxygen demand (COD) loading rate of 18 kg/m^3·d, the system demonstrated high gas production efficiency. With a bioreactor volumetric ratio of 5:5:20, the process maintained high microbial concentrations, stable alkalinity, and pH levels, particularly in the third reactor. This resulted in enhanced COD removal and methane generation, outperforming previous anaerobic systems in both energy yield and process stability [49]. A summary of conventional anaerobic biofiltration technologies and performance metrics is presented in Table 2.

Table 2 Overview of conventional anaerobic biofiltration technologies and performance metrics

Technology	Key Characteristics & Operating Conditions	Operating Conditions Performance Metrics / Highlights	References
UASB Reactor	Treats various wastewater under anaerobic conditions	Hydrogen production up to 12.3 L/L·d at 3 h HRT	[40, 41, 42]
	Performance influenced by hydraulic retention time	Pb(II) removal efficiencies of 90–100% (80–2000 ppm); max removal rate: 1948.4 mg/(L·d)	

	(HRT), influent composition, and pretreatment steps	Textile wastewater: COD removal improved from 70% (without pretreatment) to 95% (with composite coagulant)	
EGSB Reactor	Advanced variant of upflow systems designed for enhanced granular sludge stability	With 50 mg/L Fe_3O_4NPs (40–60 nm): H_2 production increased to 4.95 L H_2/d and fermentation shifted from butyrate- to ethanol-type	[43, 44]
	Improved hydraulic efficiency; additives (e.g., Fe_3O_4NPs, HAPs) further enhance performance	HAPs addition: Nitrogen removal increased from 2.8 to 13.7 gN/L·d and bioactivity reached 0.52 gN/gVSS/d	
		Pilot-scale EGSB: pH increased from 5.1 to 8.2; COD reduction of 41.1% in 4 days	
AFBR / Submerged Anaerobic Biofilter	Designed for high-strength industrial wastewaters with significant organic loads	Natural rubber wastewater: >90% COD removal with improved methane production	[45, 56, 47]
	Utilizes immobilized media and trace elements to promote biofilm development	Cassava starch wastewater: 98% COD removal and biogas production of 4.8 L/L·d at an OLR of 1.72 g/L·d and 6-day HRT	
		POME treatment: TSS removal of 68–89%; SVI between 11 and 35 L/mg; volumetric loading increased from 4.0 to 13.8 kg COD/m^3·d with reduced HRT (24 to 4 h)	
ASBR	Operates in batch mode allowing controlled process conditions	Phenol degradation: Optimal at 800 mg/L with shifts in key microbial populations (e.g., increase in Methanobrevibacter)	[48, 49]
	Efficiency highly dependent on microbial community dynamics and substrate concentrations	Three-stage ASBR for ethanol wastewater: High gas production efficiency; optimal COD loading of 18 kg/m^3·d; reactor volumetric ratio (5:5:20) leading to enhanced COD removal and methane generation	

5. Application of biochar in anaerobic biofiltration technologies

The preceding subtopics collectively accentuate biochar's diverse contributions to anaerobic biofiltration technologies. A summary of biochar applications in anaerobic biofiltration technologies is presented in Table 3. As detailed earlier, the unique porous structure and surface chemistry of biochar enable it to serve as an excellent biofilm carrier (Section 5.1) and a potent adsorbent for pollutants (Section 5.2). It also promotes microbial granulation (Section 5.3) and facilitates enhanced electron transfer (Section 5.4). Additionally, its dual function as a catalytic agent and inhibitor (Section 5.5) further highlights biochar's versatility in stabilizing and optimizing anaerobic processes. This integrated functionality not only improves pollutant degradation and resource recovery but also provides a foundation for advancing decentralized wastewater treatment systems, as explored in the sections that follow.

5.1. Biofilm carrier/support medium

Biochar functions as a high-performance biofilm carrier/support medium in anaerobic biofilters (AnBF) due to its hierarchical porous structure (143 m^2/g specific surface area vs. sand's <0.004 m^2/g) and surface chemistry. The meso-macroporous network facilitates microbial adhesion by providing microhabitats for syntrophic consortia (e.g., *Geobacter*, *Methanosaeta*) while oxygen-containing functional groups (carboxyl, phenolic) enhance hydrophilicity and electrostatic interactions with extracellular polymeric substances (EPS). This promotes robust biofilm stratification and quorum sensing, critical for stabilizing microbial consortia under variable organic loads. Biochar's roughness and pore connectivity further minimize shear-induced biofilm detachment, ensuring sustained biomass retention and metabolic activity [10].

In addition, enhanced microbial proliferation on biochar surfaces drives efficient organic degradation (e.g., COD removal >85%) and pathogen inactivation (2.27–2.38 log reductions in *E. coli*, enterococci) via adsorption and reactive oxygen species (ROS) generation. However, in warmer climates (>25°C), accelerated biofilm growth risks pore occlusion, reducing hydraulic conductivity by 30–40%. Strategic biochar particle gradation (1–5 mm) balances biofilm density and hydraulic retention, while redox-active moieties (quinones, graphitic domains) synergize with microbial electron shuttling to mitigate clogging. This dual role as a structural scaffold and biochemical mediator underscores biochar's utility in optimizing AnBF resilience and treatment efficacy in decentralized wastewater systems [50].

5.2. Adsorbent for pollutants

Sugarcane bagasse-derived biochar (BC400), synthesized at 400°C, demonstrates high efficacy as a pollutant adsorbent in anaerobic systems. With a mesoporous structure (14.3 m^2/g surface area, 3.13 nm pore radius) and oxygen-rich functional groups (-OH, C=O), BC400 achieved a BPA adsorption capacity of 32.05 mg/g via electrostatic and hydrogen-bonding interactions at pH 6.0. Freundlich isotherm (heterogeneous adsorption) and pseudo-second-order kinetics (chemisorption) govern removal. Its low-cost production and scalability (208.8 g treats 400 L) enhance integration into anaerobic biofilters for synergistic pollutant sequestration and microbial activity stabilization [51].

In a separate study carried out by Huang et. al. [52], LDH-modified biochars enhanced the adsorption of mixed heavy metals (Cu^{2+}, Co^{2+}, Pb^{2+}) and phosphate in anaerobic systems. Pristine biochars exhibit capacities of 6.9–20.7 mg/g for metals and 0.8–4.9 mg/g for PO_4^{3-}, while Mg/Al-LDH-biochars achieve 20.4–40.4 mg/g (metals) and 13.0–21.8 mg/g (PO_4^{3-}). Partial Mg^{2+} release (<7.2% of adsorbed ions) and interactions between LDH and biochar's hydroxyl/carbonyl/ether groups drive adsorption. Biochar actively contributes via C–O, C=O, and N-functional groups, challenging its role as a passive LDH carrier. Synergistic mechanisms support multifunctional pollutant sequestration in biofilters.

5.3. Granulation enhancer

Recent research highlights the beneficial role of biochar in expediting granule formation and improving reactor performance in anaerobic biofiltration systems. Ming et al. [53] investigated three types of biochar rice husk (biochar-rh), rice bran (biochar-rb), and walnut shell (biochar-ws) and found that their addition to an aerobic granular sludge system treating petroleum wastewater reduced the granulation period by approximately 15 days compared to a control. In parallel, average COD and TN removal increased by 3.2–5.1% and 10–13%, respectively, demonstrating biochar's capacity to enhance pollutant removal.

In a separate study by Wang et al. [54] focusing on anaerobic sludge granulation in two up-flow anaerobic sludge blanket (UASB) reactors, adding 4 g/L of biochar shortened the methanogenic lag time by 28.6% and increased the COD removal rate by a factor of 1.6. The granular sludge in the biochar-amended reactor exhibited a conductivity of 23.29 ± 0.99 μS/cm, nearly twice that of the control reactor, and demonstrated significantly higher integrity and hydrophobicity. Microbial community analysis suggested that biochar fosters the enrichment of Methanothrix and Geobacter species, indicating a more robust direct interspecies electron transfer (DIET) mechanism.

5.4. Electron carrier for enhanced Direct Interspecies Electron Transfer (DIET)

In an extensive study [55], biochar functionalized via microwave-assisted pyrolysis (MWP) exhibits enhanced redox properties, positioning it as a critical electron carrier for DIET in anaerobic biofiltration systems. MWP optimizes biochar's electron exchange capacity (EEC) by augmenting specific surface area (SSA) and crystallinity parameters (lateral crystallite size, La; longitudinal crystallite size, Lc), which facilitate quinone formation and graphitic domain growth. These structural modifications elevate electron accepting capacity (EAC) by 1.5–2.3-fold, driven by quinoid moieties and π-π conjugated systems, while electron-donating capacity (EDC) is amplified via oxygenated functionalities (C–OH, C=O) that mediate reductive electron transfer. The inverse correlation between average pore size and EEC underscores the dominance of surface-mediated redox reactions over pore-confined processes.

In anaerobic biofilters, MWP-biochar accelerates DIET by serving as a redox-active conduit between syntrophic bacteria and methanogens, bypassing slower hydrogen/formate diffusion. Enhanced SSA promotes microbial adhesion and interfacial electron exchange, while quinone-graphite networks stabilize charge transfer pathways. This structural synergy reduces kinetic barriers in organic pollutant degradation and methane production, aligning with the metabolic demands of complex wastewater matrices. By engineering biochar's crystallinity and functional group density, MWP enables precise regulation of electron flux, advancing biochar-integrated biofiltration as a scalable strategy for high-rate anaerobic treatment systems [56].

5.5. Catalytic agent and inhibitor

Recent research [57] on oily sludge (OS) pyrolysis has highlighted biochar's dual role as both a catalytic agent and an inhibitor in anaerobic biofiltration systems. In the context of biochar-assisted catalytic pyrolysis (BCP), biochar intensifies the degradation of recalcitrant petroleum hydrocarbons, albeit reducing the overall liquid product yield. By facilitating these reactions, biochar effectively lowers the temperature threshold required to achieve comparable removal efficiencies. As an inhibitor, biochar suppresses the emission of harmful micromolecular gases such as HCN, H_2S, and HCl, while simultaneously stabilizing heavy metals within the sludge matrix. This inhibitory effect ensures that volatile contaminants remain sequestered, mitigating potential environmental hazards during pyrolysis and subsequent anaerobic treatment.

Moreover, the resulting residue from this BCP process can be utilized as a soil amendment, providing a carbon source and essential mineral nutrients to support microbial communities in anaerobic environments. Enhanced microbial diversity and abundance contribute to improved plant germination rates and secondary removal of residual hydrocarbons. Thus, integrating biochar-based pyrolysis residue with anaerobic biofiltration technologies can streamline contaminant degradation, reduce harmful emissions, and bolster soil reclamation efforts. This multi-faceted approach underscores biochar's pivotal role in optimizing both the catalytic transformation of persistent pollutants and the inhibition of toxic byproducts, advancing a more sustainable and comprehensive waste-to-resource strategy [58].

Table 3 Summary of biochar applications in anaerobic biofiltration technologies

Application	Mechanisms / Functions	Performance Highlights / Outcomes	References
Biofilm Carrier / Support Medium	Provides a hierarchical porous structure (e.g., 143 m^2/g vs. sand's <0.004 m^2/g) for microbial adhesion	Achieves COD removal >85%	[50]
	Enhances biofilm formation via oxygen-containing groups (carboxyl, phenolic)	Pathogen inactivation (2.27–2.38 log reductions in E. coli, enterococci)	
	Reduces shear-induced detachment and supports quorum sensing	Optimizes biomass retention and treatment resilience; note: in warmer climates (>25°C) pore occlusion may reduce hydraulic conductivity by 30–40% unless particle gradation (1–5 mm) is optimized.	
Adsorbent for Pollutants	Utilizes mesoporous structures and oxygen-rich functional groups for electrostatic and hydrogen-bonding interactions	Sugarcane bagasse-derived biochar (BC400) achieves a BPA adsorption capacity of 32.05 mg/g at pH 6.0	[51, 52]
	Modified biochars (e.g., LDH-modified) enhance the binding of heavy metals and phosphates	LDH-biochars show improved adsorption capacities (e.g., metals: 20.4–40.4 mg/g; PO_4^{3-}: 13.0–21.8 mg/g)	
Granulation Enhancer	Promotes rapid granule formation by providing nucleation sites	Reduces granulation period by approximately 15 days	[53, 54]

	Improves structural integrity of granular sludge and supports DIET by enriching microbial communities (e.g., Methanothrix, Geobacter)	Increases COD and total nitrogen removal by 3.2–5.1% and 10–13%, respectively	
		In UASB reactors, 4 g/L biochar shortens methanogenic lag time by 28.6% and boosts COD removal rate by 1.6times	
Electron Carrier for Enhanced DIET	Functionalized via microwave-assisted pyrolysis to optimize redox properties	Accelerates direct interspecies electron transfer (DIET), lowering kinetic barriers in organic pollutant degradation and boosting methane production in anaerobic systems	[56]
	Increases electron exchange capacity (1.5 to.3times) via quinoid moieties and π–π conjugated systems		
	Enhances microbial adhesion and facilitates electron transfer between syntrophic bacteria and methanogens		
Catalytic Agent and Inhibitor	Acts as a catalyst to intensify the degradation of recalcitrant hydrocarbons in oily sludge pyrolysis	Lowers temperature thresholds for efficient pollutant degradation	[58]
	Inhibits the emission of harmful gases (HCN, H_2S, HCl) and stabilizes heavy metals	Reduces volatile contaminant emissions	
		Enhances microbial diversity and supports subsequent soil reclamation efforts	

6. Future perspectives

The application of biochar in anaerobic biofiltration systems for wastewater purification holds significant promise, yet several critical research avenues must be explored to realize its full potential. A primary focus for future studies should be the evaluation of long-term system performance. Current research largely relies on short-term laboratory or pilot-scale trials, which limits understanding of biochar's durability, adsorption capacity retention, and stability under continuous operation. Long-term field studies are essential to assess how biochar withstands environmental stressors, such as fluctuating wastewater compositions or hydraulic loading rates, and to determine maintenance or replacement intervals.

Another key area is the standardization of biochar production. The efficacy of biochar varies widely due to differences in feedstock (e.g., agricultural residues, wood, or sludge) and pyrolysis conditions (e.g., temperature, residence time). This variability complicates its reliable application in anaerobic biofiltration. Future research should aim to develop standardized protocols for producing biochar with tailored properties such as enhanced surface area, porosity, or functional groups optimized for specific contaminants (e.g., heavy metals, and organic pollutants). Such efforts could lead to a classification framework for biochar akin to that of activated carbon, improving predictability and performance consistency.

Furthermore, scalability is a persistent challenge that warrants attention. While laboratory results are encouraging, translating biochar-enhanced anaerobic biofiltration to industrial or municipal scales involves overcoming engineering hurdles, such as integrating biochar into reactor designs (e.g., up-flow anaerobic sludge blanket or expanded granular sludge bed systems) without compromising hydraulics or mass transfer. Large-scale pilot projects across diverse wastewater types and geographical regions would provide critical insights into practical implementation, identifying context-specific barriers and solutions.

The economic viability of biochar-based systems also requires rigorous investigation. Although biochar is often considered a cost-effective alternative to traditional adsorbents, the costs of production, post-treatment (e.g., activation or washing), and system integration must be weighed against performance benefits. Future studies should conduct detailed cost-benefit analyses, comparing biochar-augmented biofiltration to conventional methods like activated carbon filtration or chemical precipitation. Additionally, exploring circular economy approaches such as using spent biochar as a soil conditioner or leveraging biogas by-products for energy could enhance economic and environmental sustainability.

7. Conclusion

Integration of biochar into anaerobic biofiltration systems offers a versatile and sustainable approach to wastewater purification. Its ability to act as an adsorbent, support microbial activity, enhance granulation, and facilitate electron transfer positions it as a multifunctional tool capable of addressing shortcomings in traditional anaerobic treatment methods. Evidence suggests that biochar improves pollutant removal efficiency, system stability, and biogas production, making it a compelling candidate for next-generation wastewater treatment technologies.

Nevertheless, significant challenges remain; The absence of long-term performance data, inconsistencies in biochar properties, difficulties in scaling up, and uncertainties surrounding economic feasibility highlight the need for continued research. Overcoming these difficulties will require interdisciplinary efforts spanning material science, environmental engineering, and microbiology. If these gaps are addressed through extended field trials, standardized production methods, scalable reactor designs, and comprehensive economic assessments biochar-enhanced anaerobic biofiltration could transition from a promising concept to a widely adopted solution.

Compliance with ethical standards

Disclosure of conflict of interest

There are no conflicts of interest to disclose by Aramide Adenike Adesina, Isaac Uwanaobong Adeyeye, Oluwatosin Ebunlomo Okuneye, and Yusuf Temitope Abdulkareem in publishing this manuscript.

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