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Design and performance evaluation of biochar biofilters for industrial wastewater treatment

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ABSTRACT

The use of biochar biofilters as a sustainable solution for industrial water remediation has become popular. This review presents a summary of existing works on the use of biochar filters for industrial effluent. Factors like design, hydraulic performance, and mechanical durability have been explored. For filter design, key reactor parameters like empty bed contact time (EBCT), hydraulic load ratio (HLR), bed depth, and media configuration were reviewed. The parameters were found to have a significant effect on pressure drop, clogging mechanisms, and backwash requirements. Similarly, the mechanical properties of biochar media, like density, hardness, and attrition resistance, were affected by head loss, media lifespan, and regeneration capability. Case studies like textile pharmaceutical industries and stormwater effluents revealed reductions in colour, heavy metals, and refractory organics. Practical design workframes are provided for scaling systems from laboratory columns to pilot and full-scale levels. EBCT-based sizing, media selection, parallel module operation, and breakthrough monitoring are emphasized for multiscale designs. Regeneration techniques were evaluated in relation to lifecycle durability and end-of-life handling. It was shown that biochar biofilters are suitable for effluent polishing with appropriate hydraulic design, especially when EBCT exceeds 15 minutes. The main remaining challenges that were identified are the control of long-term fouling, standardization of filter-grade biochar, and balancing adsorption capacity with permeability. In future studies, automated fouling control, standardized specifications for filter-grade biochar, and composite media designs that balance adsorption efficiency with hydraulic permeability should be explored.

Keywords: Biochar Biofilters, Circular Economy, Heavy Metals Removal, Industrial Wastewater Treatment, Regeneration

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I. INTRODUCTION

Industrial effluents from various sectors like textiles, dye manufacturing, metal finishing, and chemical processing yield high pollutant loads that are challenging to treat. Their main contaminants include persistent organic dyes, heavy metals, toxic organics, and other harmful chemicals (Ali Alshehri & Pugazhendhi, 2024; Hikmat et al., 2026). Conventional treatment methods have proven to be costly and generate secondary waste (Alsawy et al., 2022), hence the need for more sustainable solutions. In this context, biochar, a high-carbon-content material produced through biomass pyrolysis, is gaining popularity as a sustainable adsorbent. Biochar posseses high porosity, surface functional groups, and affinity for a range of pollutants, making it a cheaper alternative to activated carbon (Yaashikaa et al., 2020). Biochar can be synthesised from waste biomass, hence promoting the circular economy and waste-to-resource objectives.

Recent studies and reviews have highlighted the effectiveness of biochar in adsorption for contaminants like organic compounds, nutrients, and heavy metals (Alsawy et al., 2022). For instance, biochar has been efficient in adsorbing synthetic dyes from textiles, mostly achieving high colour removal capacity (Hikmat et al., 2026). Biochars rich in oxygen-containing functional groups have been found to bind metal ions (Tan et al., 2021). Such biochars are recommended for effluents with dissolved heavy metals. The performance of biochar-based filters in pollutant removal approaches that of commercial activated carbons. The biochar filters perform effectively when the biochar is produced under optimized conditions or activated either chemically or physically to enhance porosity (Liu et al., 2017). Batch adsorption has been greatly used for biochar-based systems but are labour and time intensive. Therefore, the exploration of the use of biochar in flow-through systems for continuous treatment of industrial effluents is beneficial to bridge the gaps. Biochar filters are increasingly becoming a promising replacement or complement to sand and activated carbon filters since they have proven effective in onsite trials (Perez-Mercado et al., 2018).

Despite this promise, implementing biochar filters requires careful engineering design. Many studies focus on the chemical aspect but have not addressed the mechanical and hydraulic considerations. For instance, recent studies on attrition (Wang & Sedighi, 2023), backwashing (El Barkaoui et al., 2025), (Slavik et al., 2013), and hydraulic pressure drop (Pap et al., 2025; Rangabhashiyam et al., 2022)highlight the need to integrate mechanical and hydraulic design into biochar filter development. The understanding of these properties will go a long way to help in maintaining their long-term performance (Mian et al., 2023). Design protocols for regeneration and replacement of exhausted biochar need to be established to make the technology sustainable and economically viable.

1.1 Research Objectives

i. To evaluate design and performance parameters of biochar biofilters,
ii. To assess industrial applications and deployment potential of biochar filters for industrial wastewater.
iii. To examine regeneration strategies of biochar filters and assess future challenges.

II. LITERATURE REVIEW

2.1 Theoretical Framework

This section outlines the theoretical basis for biochar biofilters, focusing on material properties, preparation methods, and the mechanisms that facilitate pollutant removal. Biochar is typically produced by the pyrolysis of biomass feedstocks (Alsawy et al., 2022). The pyrolysis conditions and feedstock type strongly influence the physical and chemical properties of the resulting biochar. Generally, biochars have a carbon-rich porous structure with considerable internal surface area and a matrix of functional groups on their surface (Tan et al., 2021), making their characteristics variable (Xiang et al., 2020). For instance, in one comparative study, several biochars produced from different biomasses had surface areas of 100–300 m^2/g, and reached up to 1000 m^2/g, after activation (El-Sawaf et al., 2026). Sand had only 0.15 m^2/g.

To accommodate larger molecules and particles, biochar typically has a pore structure dominated by mesopores and macropores, especially at lower pyrolysis temperatures. Depending on the feedstock, it may also contain inorganic ash components. Since biochar has a substantially lower bulk density than sand, it is easier to handle but can create buoyancy in water and media loss during heavy flows or backwashing, necessitating careful containment and design. Studies frequently utilise biochar particle sizes comparable to sand (1-2 mm) or blend biochar with sand or gravel to balance stability and performance. This preserves strength and permeability while improving pollutant removal (Maleki Shahraki & Mao, 2022). The feedstock type greatly influences all biochar properties.

Table **1** reveals that hardwood biochars have higher surface area and lower ash content, while biosolid and animal waste biochars have higher ash and density (Bednik et al., 2022) (Boraah et al., 2023). The most suitable particle sizes are also recommended.

Table 1

Biochar properties according to feedstock type (Maleki Shahraki & Mao, 2022), (Bednik et al., 2022)

Feedstock	Surface area (m^2/g)	Density (kg/m^3)	Hardness/attrition (%/yr)	Ash content (% d.w.)	Recommended particle size (mm)
Softwood	300–500	180–250	<5	<6	1–2
Hardwood	500–800	200–300	<5	<8	1–2
Agricultural residue	600–900	300–400	<4	<12	0.5–1
Biosolid	150–250	400–600	<5	20–40	0.5–1
Animal waste	250–350	300–500	6–15	10–20	0.5–1

2.2 Empirical Review

This section is based on the theoretical framework to review empirical evidence from laboratory, pilot studies, and field studies. It highlights how biochar biofilters have been applied across different industries, proving its versatility.

2.2.1 Textile and Dye Industry

Industrial textile effluents are persistent in colour (dyes), among other chemicals. Biochar has been extensively researched for dye removal, demonstrating high efficiency in the removal of various dyes such as Congo red (Ahad et al., 2025). Biochar has been confirmed as a viable adsorbent for both cationic and anionic dyes. (Hikmat et al., 2026). One advantage is that biochar can be tailored to target specific dye classes (Fuhr et al., 2025; Hashemi et al., 2024) . During design, textile effluents with high suspended solids would require pre-filtration to prevent rapid clogging of the biochar bed (Das & Mishra, 2025). When implemented as a polishing step, biochar filters could bring down dye concentrations to meet discharge norms for colour. For instance, a laboratory column packed with sludge-derived biochar achieved complete decolourisation of a model azo dye (Harja et al., 2022).

2.2.2 Metal Plating and Mine Wastewater

Industrial wastewater with heavy metals is considered for remediation using biochar biofilters (L. Wang et al., 2025). Biochar made from animal waste, wood, and sludge has demonstrated a strong affinity for heavy metals (Ambaye et al., 2021). Similarly, fixed-bed column studies concluded that biochar can remove metal ions for several bed volumes before breakthrough, although the competing ions can reduce adsorption capacity (Kumkum & Kumar, 2024). A similar study on industrial waste-derived biochar concluded that biochars have the capacity to effectively treat heavy metal–contaminated wastewater (Meftah et al., 2025; Okoro et al., 2025). During design, metal-laden biochar filters must be operated with regulated flow rates to maximize contact time (Bulacio Fischer et al., 2025). One practical example is the use of biochar to treat stormwater from galvanized surfaces. Field trials indicated that biochar-amended filters consistently captured dissolved metals better than conventional sand filters (Roy & Bharadvaja, 2021; Scaling Up Biochar, 2023.).

2.2.3 Chemical and Petrochemical Effluents

Biochar's broad-spectrum adsorption can complement biological treatment in oil removal. For instance, biochar filters have been tested for refinery wastewater polishing and shown improvements in removing residual oil (Nishshanka & Silva, 2025). In one high-rate filtration study, biochar media outperformed sand/anthracite in removing colour and turbidity from chemically treated raw water (Almutairi et al., 2023; García-Ávila et al., 2023). While that study was focused on drinking water production, the results are promising for chemical effluents that often have colour/organic residues (Cescon & Jiang, 2020). Since chemical sector wastewaters contain toxic organics that inhibit microbial processes, a biochar filter is recommended as a pre- or post-treatment barrier to polishing the effluent before discharge (Ghazal et al., 2022).

2.2.4 Food and Pharmaceutical Industry Effluents

These often contain high COD, nutrients, and trace organic. Biochar can be both an adsorptive and a support medium for biofilms. Anaerobic biofilters packed with biochar have been deployed for food industry wastewater, utilizing biochar to improve methane production and effluent quality (Enaime et al., 2020; Kaetzl et al., 2019; Karić et al., 2022). The biochar provides surface area for anaerobic microbes and adsorbs inhibitors. In pharmaceutical wastewater, biochar has been used for removing antibiotics and endocrine-disrupting compounds (Chu et al., 2025; El-Sawaf et al., 2026) However, life-cycle considerations are key since these spent biochars will carry the adsorbed pharma compounds and must be regenerated or disposed of safely (Palansooriya et al., 2020; Shah et al., 2020). The following sections will examine how to design systems to exploit biochar's capabilities while ensuring the filter operates reliably.

III. METHODOLOGY

This review followed a structured, reproducible literature search designed for engineering synthesis. Searches were performed across Scopus, Web of Science, and Google Scholar for publications from 2000 to 2025. Inclusion criteria prioritized studies that reported experimental or field data, while single-sample descriptive reports were excluded. Extracted data were categorized by study scale as laboratory, pilot, or field. Evidence strength was graded as high, medium, or low based on sample size, duration, and whether results were replicated. Synthesis emphasized quantitative ranges, typical operational practice, and gaps where data were sparse.

IV. FINDINGS & DISCUSSION

4.1 Reactor Configuration and Sizing

Biochar filters may be used in different configurations, such as mixed media filters (e.g., biochar plus sand), porous reactive barriers or beds (for groundwater flow), and stacked bed columns (for upstream or downstream flow). The simplest configuration is a column of downflow where the wastewater flows through a cylinder filled with granular biochar, either by gravity or pressure. In larger-scale systems, it is often necessary to arrange several columns or filter cells in parallel to cope with higher flow rates. The bed depth is a critical parameter - deeper beds provide longer contact time and greater capacity before the intrusion occurs, but also cause a greater pressure drop. Commonly, biochar columns at laboratory scale use bed depths of 0.5 m to 1 m (Dalahmeh et al., 2016), equivalent to typical activated carbon or sand filters.

4.1.1 Empty bed contact time (EBCT)

EBCT is the nominal time that the liquid element would spend in the reactor if the bed were empty. It is a useful construction parameter for adsorbing filters. Longer EBCT generally increases the removal efficiency of the adsorption process (Tadesse et al., 2025). However, a longer EBCT leads to a larger volume of filters per flow and thus higher costs. For biochar filters, studies indicate that an EBCT of 15 to 30 minutes is often required to effectively remove pollutants (Akcay et al., 2016). For example, a column phosphate removal study achieved a breakthrough (Eq. $P<0.1$ mg per L) after 192 hours of treatment with 30 min EBCT, compared to a faster breakthrough with shorter EBCT (Gopinath et al., 2021; Pap et al., 2025; Rangabhashiyam et al., 2022). Another review concluded that EBCT for longer than 15 min is preferable for long-term applications where maximisation of adsorption capacity and consistency is important (Fundneider et al., 2021). On the other hand, in applications with high flow rates, the EBCT could be as low as 5 to 10 min, trading some efficiency for throughput (Al-Malack & Anderson, 1997). Therefore, in order to ensure a thorough disposal and avoid frequent media depletion, designers should consider longer EBCT for industrial waste streams with high loads.

$$EBCT(\text{min}) = \frac{Bed\ \text{Volume}(\text{m}^3)}{flow\ rate(m^3/h)} \qquad 1$$

To size a biochar filter, one can use equation 1 to compute the polishes constituting the biochar bed. Equation 2 shows the relationship between HLR, EBCT, and Bed depth.

$$HLR = \frac{Bed\ depth}{EBCT} \qquad 2$$

The relationship between EBCT, hydraulic loading rate, and bed depth is summarized in Figure 1, which provides a practical mechanical design framework for biochar-based biofilters. The hatched zones are defined by the first principles of EBCT, HLR, and bed depth, defining conditions which ensure an adequate contact time without excessive hydraulic resistance and exclude regimes susceptible to premature rupture due to lack of residence time.

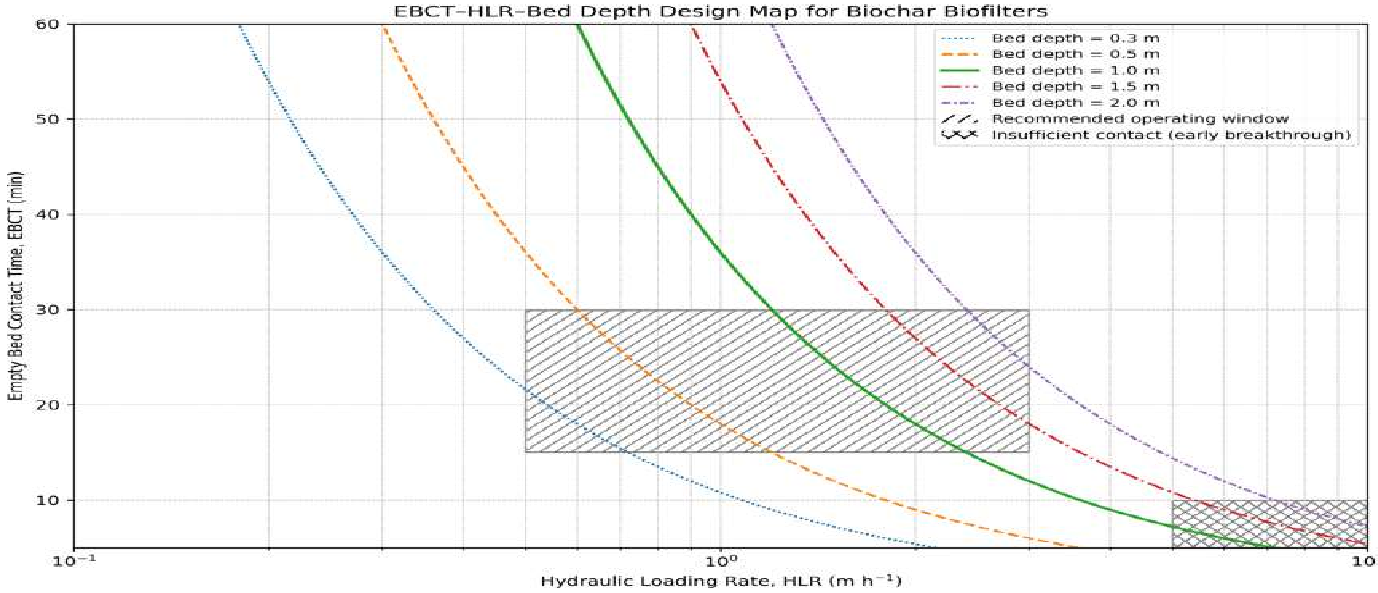


Figure 1
EBCT–HLR–bed depth design map for biochar biofilters (Rangabhashiyam et al., 2022)(Gopinath et al., 2021).

4.1.2 Bed Depth and Configuration

As shown in Figure 1, increasing EBCT at a given HLR requires a correspondingly deeper bed. A deeper bed not only increases the mass transfer but also accelerates the rate of pressure loss and the frequency of backwash. High adsorbable contaminants may be completely removed in the upper part of the bed until the medium is saturated, while less adsorbable contaminants may penetrate further. Therefore, for a given influent and biochar, the minimum depth of the bed is required to achieve the target concentration of the effluent. For biochar filters designed to support biofilms, the bed depth is usually up to 0.5-1 m. (Duran-Ros et al., 2023). Unsaturated operation in filters, such as biochar-amended soil filters, leads to significantly longer effective contact times compared to saturated filters. For instance, activated biochar filters can have a mean hydraulic residence time of approximately 4.9 days, whereas saturated sand filters only achieve about 0.5 hours. This highlights the distinction between flow-through contact time (EBCT) and effective contact time influenced by water retention. In industrial systems, filters are typically designed to operate in a saturated state for better control, focusing on EBCT. However, when designing infiltration beds with biochar for low-flow use, the actual retention may considerably exceed the calculated EBCT due to water retained in pore structures.

Table **2** summarizes the start values and is recommended for biochar filter parameters.

Table 2
Typical Design Ranges and Recommended Start Values for Biochar (Duran-Ros et al., 2023)

Parameter	Unit	Typical range (reported)	Recommended start value
EBCT	minutes	5–60	15–30
HLR	m/h	0.1–10	0.5–3.0
Bed depth D	m	0.3–1.8	0.5–1.5
Particle size (effective)	mm	0.5–4.0	1–2
Packing porosity ε	—	0.50–0.75	0.55–0.70

4.1.3 Biochar upscaling pathway using EBCT, HLR and bed depth

Upscaling a biochar treatment system from pilot to full scale is best approached through linking hydraulic and geometric parameters

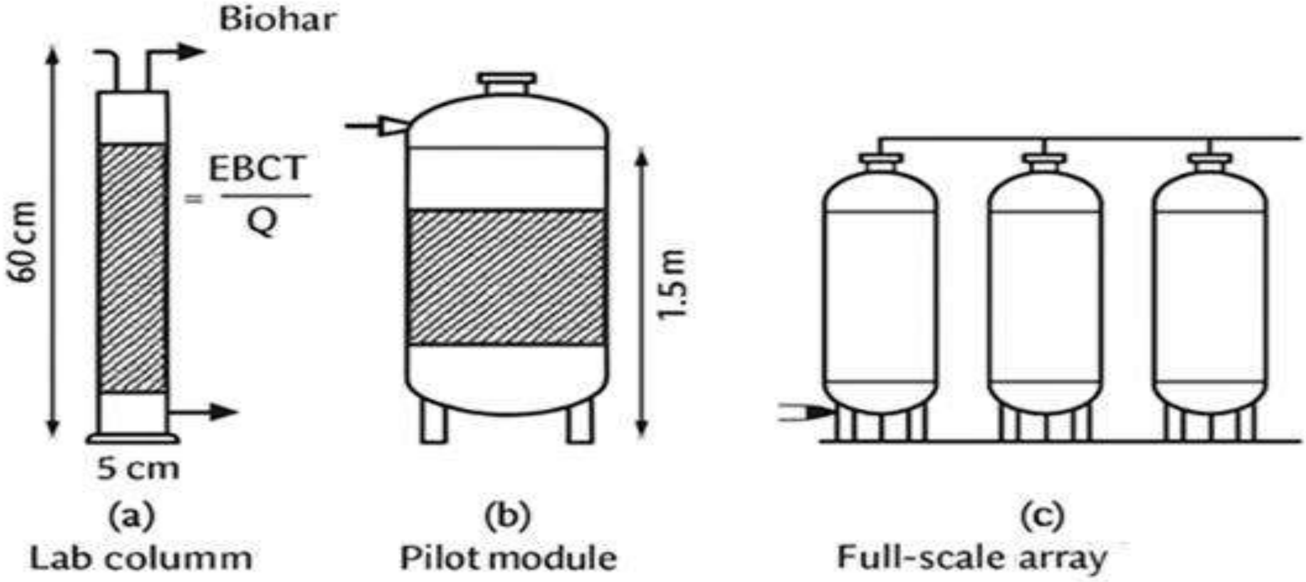


Figure 2
Laboratory-to-full-scale upscalling pathway (Eniola & Sizirici, 2023)

Figure 2 outlines the laboratory-to-full-scale upscaling pathway applied throughout this review. Figure 2 (a) is a standard laboratory column, with representative dimensions of 5 cm diameter and 60 cm bed depth. It is used to determine EBCT and generate breakthrough curves. Figure 2 (b) shows a typical pilot-scale unit with a 1–2 m bed depth, employed to confirm head loss development, backwash requirements, and media attrition under site-specific effluent conditions. Figure 2 (c) illustrates a full-scale system comprising multiple parallel modules, sized using equation 1. This figure should be used to translate laboratory EBCT results into pilot and full-scale bed volumes and to guide the selection of HLR and module numbers for continuous operation. Typical starting values for EBCT and HLR are summarised in Table 2. Literature and pilots suggest EBCT on the order of tens of minutes and HLR of fractions of m/h to a few m/h are effective starting points for many industrial waste applications (Eniola & Sizirici, 2023). Each use case should, however, verify these via bench tests, as different biochars and effluents may deviate.

4.1.4 Breakthrough Behavior and Concurrent Pressure Differential ΔP Response

Breakthrough behaviour and differential pressure rise are complementary indicators of biochar bed performance. Breakthrough reflects the media capacity exhaustion and increasing ΔP signals hydraulic fouling. Monitoring both simultaneously allows operators to distinguish between chemically driven breakthrough under stable hydraulics and premature breakthrough caused by rising head loss and reduced effective EBCT (Trivedi et al., 2025). The results enable timely backwashing, flow control, and media replacement. Figure 3 shows Breakthrough behavior in biochar biofilters is significantly influenced by design parameters. Longer empty-bed contact times (EBCTs) result in delayed breakthrough and smoother curves, indicating better flow and utilization of adsorption capacity, whereas shorter EBCTs lead to quicker performance loss. Pressure drops increase over time due to solids accumulation, which is controlled through backwash triggers. Since chemical breakthrough and hydraulic fouling often occur independently, optimal biofilter design should integrate EBCT performance targets with pressure-drop monitoring and backwash control to ensure efficiency and long-term stability (Ang et al., 2020).

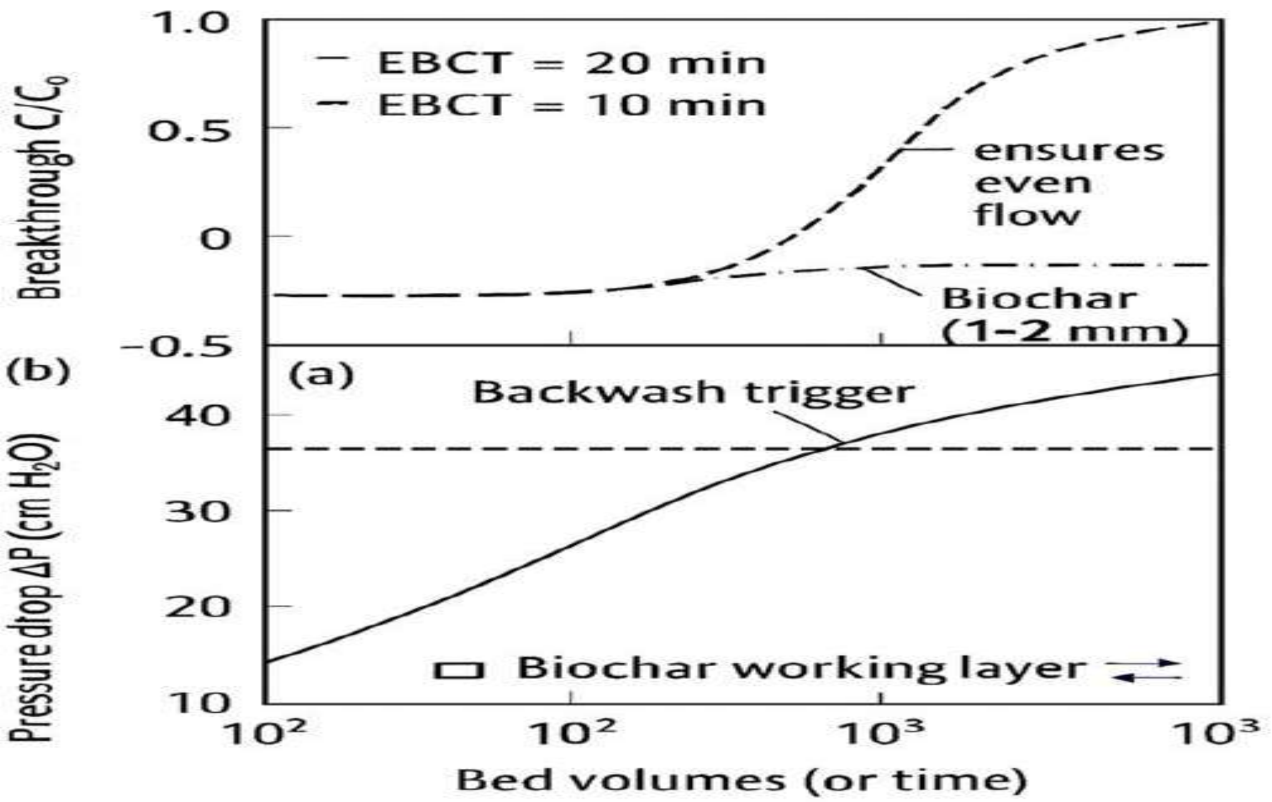
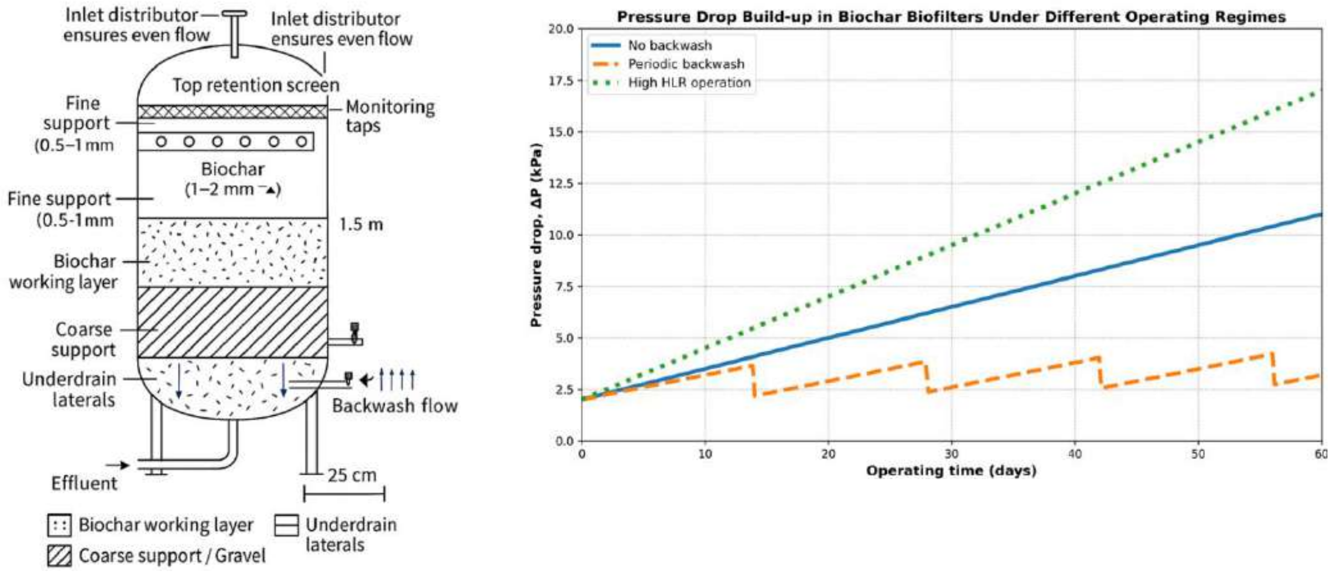


Figure 3
Example Contaminant Breakthrough (Ang et al., 2020; Trivedi et al., 2025).

4.1.5 Hydraulic Behaviour of Biochar systems

Hydraulic behaviour governs the performance of packed-bed biochar systems by controlling flow distribution, pressure drop, and clogging. Uniform flow is essential to preserve effective EBCT (Pap et al., 2025; Rangabhashiyam et al., 2022). Pressure drop is reliant on flow rate, bed depth, particle characteristics, and solids accumulation. Clogging arises from suspended solids capture, biological growth, and fines migration, reducing permeability (Tadesse et al., 2025). Figure 4a shows a detailed cross-section of a packed-bed biochar filter. The inclusion of monitoring taps and differential pressure ports emphasises routine operational checks through ΔP monitoring and sampling at the inlet, mid-bed, and outlet, and the schematic should be used to define the geometry of biochar filters to increase efficiency and minimise biochar attrition (Gopinath et al., 2021). Figure 4b on the other hand, shows the accumulation of pressure drop in the biochar biofilter under the different operating regimes. Continuous operation without backwash results in a monotonic increase of hydraulic resistance, while regular backwash partially restores the permeability and increases the hydraulic pressure loading speed, accelerating the accumulation of pressure loss due to increased drag and water catch (H. Wang et al., 2020).



(a) (b)

Figure 4
(a)Schematic view of a packed bed Biochar filter, and (b) Pressure drop build-up in biochar biofilters under different operating regimes (Pap et al., 2025; Rangabhashiyam et al., 2022).

4.2 Mechanical Properties and Durability of Biochar Media

The mechanical durability of biochar particles is dependent on feedstock and pyrolysis conditions. Durability is important in the design of biochar filters. This property is essential for withstanding the weight of overlaying media, hydraulic shear pressures, and impacts during backwashing. Mechanical durability is dependent on the following factors:

4.2.1 Attrition in operation

Biochar filters undergo attrition under water flow. Continuous but slow mass loss from both biochar and activated carbon(AC) granules was observed (Wang & Sedighi, 2023). The loss indicates that bits of the media were wearing off with time. Interestingly, hardwood biochar lost mass at a rate comparable to activated carbon, implying that a well-made biochar can be as physically stable as AC in certain conditions. It was found that impurities in biochar might flush out preferentially. This can create new Interstices inside the granule, but those impurities end up in the effluent unless filtered out. It was suggested that when these impurities dissolve, they facilitate the co-transport of contaminants that were bound to them. (Buss et al., 2022).

4.2.2 Impact of Backwashing

Backwash is a more vigorous process than filtration flow and can cause attrition due to inter-particle collisions. Media that survive filtration might still break down after repeated backwash cycles. A small percentage of biochar media is lost during each backwash (Slavik et al., 2013). Designers could compensate by slightly overfilling beds initially and monitoring media loss. The lower density of biochar means collisions impart less, which may reduce breakage compared to heavier media collisions. However, extra abrasion may result from the effect of air bubbles and turbulent two-phase flow when air scour is applied (Turan, 2023).

4.2.3 Structural Integrity Under Load

In deep beds, the bottom layers of media bear the weight of the media above, plus the water head (Ives, 1985.). Biochar, being lightweight, exerts a pressure of approximately 0.2–0.3 g/cm² on the bottom layer at a height of 1 meter, in contrast to around 1 g/cm² for sand. This implies a minimal risk of crushing under reasonable bed depths. Biochar’s thermal stability is generally maintained at ambient conditions. However, designers must take caution for the treatment of hot effluents exceeding 50 °C. Elevated temperatures may lead to thermal expansion and potential desorption of pollutants, despite biochar's stability at high temperatures in inert environments (Barbusinski et al., 2017).

4.2.4 Leaching and Chemical Durability

Durability encompasses how the media chemically holds up. Some biochars, especially those from waste biomass, contain heavy metals or other potential leachates intrinsically (Tian et al., 2025). For example, sewage sludge biochar can contain metals like Zn, Cu, Pb, etc., that were in the sludge. Ideally, these are in stable mineral forms, but changes in water chemistry (pH, redox) could leach them. It has been observed that pyrolysis can stabilize many heavy metals in a less leachable. Moreover, a very acidic influent could extract metals from biochar (Cao et al., 2024a). Providentially, most industrial effluents requiring biochar are not extremely acidic by the time they reach the filter since neutralization is commonly done upstream. Periodic testing of effluent for any leached constituents is recommended, especially during initial filter rinse-up.

4.2.5 Mitigation of Attrition

To improve biochar hardness, several approaches exist. Using higher pyrolysis temperatures can create a more carbonized, less friable char structure (Masara et al., 2026). Some producers pelletize or briquette biochar with binders to make uniform hard granules (Jjagwe et al., 2021). Others perform chemical treatments that not only add functionality but also improve on biochar strength. There is a tradeoff between porosity and activation since activation processes that introduce porosity can weaken the structure. (as they remove carbon mass internally), so there's a trade-off: highly activated biochar (with very high surface area) might be less robust physically. For instance, activation creates many inner pore channels and can reduce the particle's mechanical strength (Elnour et al., 2019). Therefore, for applications requiring extensive backwashing and long life, a slightly less-activated but structurally stronger biochar is suggested over an extremely porous but brittle one.

4.2.6. Media Replacement Frequency

The replenishment of biochar media has become a great concern, especially the replacement due to attrition rather than adsorption saturation. Field data is limited due to recent deployments of biochar filters (Laishram et al., 2025). Compared to GAC filters, which are usually replaced every 3–24 months based on usage, biochar may saturate sooner for some pollutants, limiting multiple reuse cycles (Huggins et al., 2016). To ensure mechanical durability of a biochar filter: (1) select a biochar with high hardness, (2) avoid excessive shear in handling, (3) incorporate gentle backwash protocols, and (4) monitor for excessive pressure drop.

4.3 Design Workflow and Scale-Up Considerations

Designing a biochar biofilter for industrial effluent involves a multi-step scale-up process from laboratory tests to pilot and full-scale implementation (Fang et al., 2025). A recommended workflow is as follows:

4.3.1 Laboratory Treatability Tests

Biochar's adsorption capacity for key pollutants is tested through batch adsorption tests for the target wastewater. Follow the batch tests with column experiments at lab scale, as illustrated in Figure 1, to measure breakthrough curves. In these tests, use actual or simulated effluent to capture the effects of the water matrix (Jia et al., 2023). For instance, a lab column might be run at different flow rates to see the effect on the dye to select the best-performing one for the specific effluent (Chu et al., 2025).

4.3.2 Media Selection and Specification

Based on the lab results and availability, choose a biochar grade for scale-up. Specify parameters like particle size distribution, bulk density, hardness, and ash content. If the application is the removal of metals or phosphate, a biochar with known higher mineral content is preferred. For primarily organic adsorption, a high-carbon, high-surface-area biochar is preferable.

4.3.4 Pilot Testing

A pilot filter test should be conducted on-site. This could be a column treating a side stream of the actual wastewater. The pilot should run for an extended period to evaluate real-world fouling, daily variations in water quality, and operational issues. Breakthrough time for critical contaminants, head loss progression, frequency of backwash needed, media loss, and effluent quality should be determined frequently. Pilot tests in one study showed that biochar filters in parallel with sand had better nutrient removal and could handle higher load variations without failure (Fu et al., 2017). Pilots will allow refinement of the backwash procedure by determining the minimal fluidization velocity for the chosen biochar and the duration of backwash.

4.3.5 Scale-Up Design

The pilot data should be used to scale to the full treatment flow by adding parallel larger units. During cross-sectional scaling, the flow characteristics and ECBT must be maintained. Often, multiple moderate-sized modules are recommended over one huge bed to provide easier control. For example, to treat 100 m³/h, one might design four parallel biochar filters, each with a 25 m³/h capacity. This way, one can backwash one unit at a time while others continue treating (Sayago, 2023).

4.3.6 Integration into Treatment Train

A Decision should be made on where the biochar filter will be fitted in the treatment process. For a highly contaminated effluent, biochar filtration will be a polishing step after primary and secondary treatment. In a textile mill, for instance, one might have: *equalization -> chemical coagulation -> sedimentation -> biochar filters -> final UV or oxidation.* The placement of the biochar unit after removing bulk solids and readily degradable matter ensures the char's capacity is primarily for stubborn pollutants like dyes. This improves cost-effectiveness (*Biochar Water Filtration: The Natural Solution Alberta Farmers Are Using to Purify Farm Water - Organics Farming, The Canadian Way*, 2025.). When the biochar filter is deployed as a primary filter, clogging will be common, and regular replenishment of the media is desirable.

4.3.7 Control and Automation

Full-scale biochar filters should incorporate controls similar to conventional filters. The controls include flow control valves to maintain the target hydraulic loading rate (HLR), differential pressure sensors for triggering backwash during high head loss, and water quality monitors for detecting breakthrough. Backwash systems must be engineered for the biochar's properties to achieve a bed expansion of approximately 20-30% (Jevremovi & Nedi, 2025). Automated backwash can be implemented based on a timer or a differential pressure threshold.

4.4 Media Regeneration and Lifecycle Durability

4.4.1 Regeneration Techniques for Biochar Media

The use of biochar as a sorbent is advantageous since it presents the possibility of **regenerating** the media and reusing it for multiple treatment cycles (Jevremovi & Nedi, 2025). Figure 5 presents a decision tree to guide the selection of regeneration or end-of-life options for spent biochar. The main determinants of the decision include: contaminant class, economic recovery potential, and site capabilities. Effective regeneration can significantly reduce operational costs and waste generation by extending the life of the biochar media (Anderson et al., 2025).

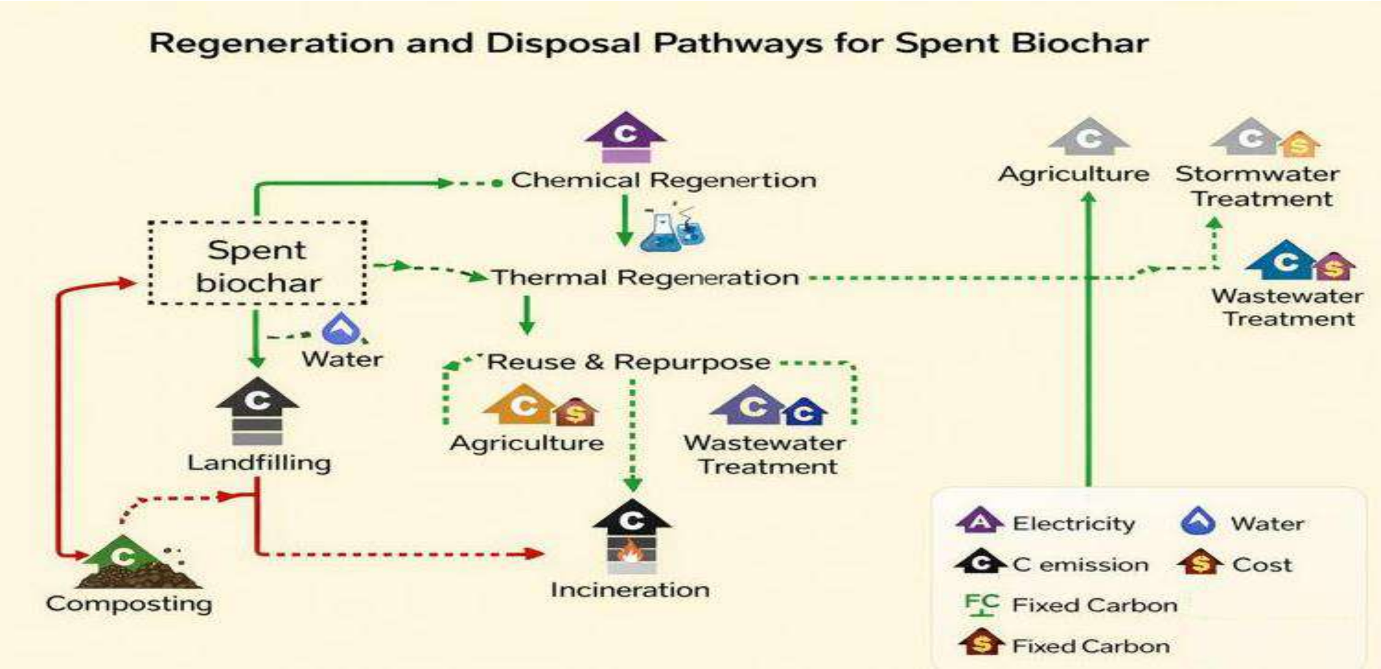


Figure 5
Regeneration and Reuse pathways for spent biochar (Anderson et al., 2025.; Baaloudj et al., 2025; H. Tan et al., 2023)

4.4.2 Thermal reactivation

Biochar, similar to GAC, can be thermally regenerated by heating to temperatures between 300–800 °C to volatize and oxidize organics. It is normally done in a controlled atmosphere to prevent decomposition of the biochar (Jia et al., 2023). Thermal regeneration is effective for many organic and inorganic contaminants since inorganic ones do not volatize with heat. It's noted that such high-temperature regeneration can be costly – it may constitute up to

50% of the cost of new biochar production. Thus, it is usually viable only for expensive biochar. Thermal regeneration causes a slight loss of biochar mass and distorts pore structure in each cycle, hence lowering the lifecycle (San Miguel et al., 2002).

4.4.3 Chemical regeneration

Chemical regeneration has become popular since it can be performed in situ and at a lower temperature. It involves flushing the spent biochar with a chemical solution that extracts the pollutants. The choice of chemical depends on the pollutant: acidic organics or dyes, heavy metals, and basic organics. A recent review highlighted that chemical regeneration is the most widely applied due to its preservation of the adsorbent and relatively mild conditions (Baaloudj et al., 2025) For example, researchers have demonstrated multiple cycles of dye adsorption and desorption using NaOH or alcohol as regenerants with only slight loss in capacity each time (Tan et al., 2023).

4.4.4 Biological regeneration

For a continuously operated biofilter, microorganisms can metabolize adsorbed compounds to achieve regeneration. For example, when a biochar filter adsorbs a biodegradable substance, the biofilm on its surface consumes it to free up that adsorption site. This is the principle behind Biological Activated Carbon (BAC) filters, where ozone-oxidized compounds are adsorbed and biodegraded in situ. This process is passive and continuous, but is limited to the biodegradable fraction and is hard to quantify (Baaloudj et al., 2025).

4.4.5 Regeneration in Practice

Industrial deployment of regeneration will depend on scale and pollutant value. If the adsorbate is valuable or hazardous, there is a need for regeneration to recover it. For example, gold or silver adsorbed on biochar from mining wastewater should one could be stripped with acid to recover metals. In dye recycling contexts, desorbing dyes with a solvent for reuse could be viable. Similarly, if the adsorbates are mixed toxins, regeneration could only be done with the intent to reuse the char, and the spent regenerant must then be disposed of properly. For metal-laden char, acid regeneration yields a metal-rich solution that could be treated by precipitation to yield a sludge or possibly electrolysed to recover metals. Regeneration should not create new problems like significant leaching of char or massive chemical use. Another review notes that integrating regeneration to make biochar treatment truly sustainable; otherwise, disposing of and re-synthesising biochar repeatedly could become resource-intensive (Alsawy et al., 2022). The research on green, sustainable regenerants is emphasized.

4.5 Media Longevity and Lifecycle Management

The lifecycle of biochar filters includes the media's adsorption capability and physical integrity, as well as its disposal at the end of its useful life. Key considerations include the number of adsorption/regeneration cycles, the effects of aging on performance, and final disposal or reuse of spent biochar.

4.5.1 Service Life in Filters

In the single-use scenario, the service life of the biochar bed is up to the target pollutant breakthrough (Speksnijder et al., 2025). Depending on the pollutant load, this can range from days to years. For example, if the biochar capacity is 100 mg of dye per day and the loading is 10 mg of dye per 200 days of run, then 1 m of biochar (200 kg) can be treated in the order of (capacity × mass + loading) = (100 mg of g × 200 000 g) + 10 mg of dye per day = 2 000 000 l = 2 000 000 l. However, the actual performance would depend on the adsorption kinetics and the multi-component effects. The durability of the medium is extended to several cycles in the case of regeneration. The total volume treated could be five times the volume treated per cycle before the medium is considered to be exhausted or too degraded, provided that biochar can be regenerated five times with little loss of capacity, as some studies suggest (Fouda-Mbanga et al., 2024).

4.5.2 Aging and fouling

Even if target pollutants are removed and the media is regenerated, other foulants such as natural organic matter (NOM) may slowly coat the biochar. The fouling reduces biochar’s capacity over time and cannot be completely reversed by standard regeneration. Backwashing only dislodges physical deposits to some extent, but very fine pore deposits or strongly bound organic films may remain. Therefore, an "aged" biochar may exhibit 10-20% less adsorption efficiency than fresh, even if target adsorbates were removed after each cycle. Additionally, structural aging may result from oxidation from leftover or the repeated wetting and drying cycles during operation (Fouda-Mbanga et al., 2024). However, unless there are extreme circumstances or chemicals exist, biochar is resistant to degradation, and there is little chance of a significant structural change on the timescale of filter use.

4.6 End-of-Life Options

When the biochar media is no longer effective or is too clogged, it must be removed and managed. The possible ways of using biochar include:

4.6.1 Thermal Destruction (Incineration)

Any hazardous organic contaminants on the spent biochar can be destroyed by incineration or pyrolysis. The inorganic pollutants on the char will turn into ash, which needs to be disposed of. If done in an energy recovery unit, burning biochar can offset some fuel because it recovers some energy, similar to burning charcoal (Cao et al., 2024b).

4.6.2 Landfill Disposal

Spent biochar can be treated as solid waste in a landfill. However, if heavy metals exceed regulatory thresholds, they may be considered hazardous waste and must be specially landfilled with leachate control. Organic-loaded biochar may be nonhazardous and can be landfilled in a conventional way (Cao et al., 2024b). It may be used as a sorbent for other components of the leachate, but it will eventually degrade. *Beneficial re-use*: Spent biochar can be reused in secondary applications, such as slow-release fertilizer made of phosphorus-loaded biochar, biochar with organic adsorbates used as fuel in a cement kiln, and metal-laden biochar as aggregate in building material. If the metals are embedded in a concrete matrix, leaching will not occur (Praneeth et al., 2022).

4.7 Case Studies and Industrial Deployment

In this section, some case studies will be highlighted. Practical considerations for deploying biochar biofilter systems in industrial contexts will be discussed, and how the principles are applied in practical applications.

4.7.1. Case Study 1: Textile Mill Effluent for Colour Removal.

Bio-filtration was deployed as a polishing step to reduce residual dye colour in treated waste water. Conventional treatment in the plant has reduced COD and solids, but has left around 200 ADM units of colour, which exceed discharge limits (Kornaros & Lyberatos, 2006). The downflow steel pressure vessel with a volume of 1 m³ was filled with biochar from locally produced rice husks. Biochar had particle sizes ranging from 1 to 3 mm and a surface area of up to 300 m2 per g. The EBCT design was 60 minutes with a flow rate of 1m³/h. In the first operation, the colour of the wastewater was reduced by 95 percent (to <10 ADMI) by the biochar filter, and the biochar also adsorbed some of the refractory COD and contributed to further reducing the BOD. The pressure drop started at 5 kPa and gradually increased to 30 kPa over a period of two weeks, during which 300 m³ of waste was treated with air and water, some of which restored the head loss to 10 kPa. The filter was running for three months before a significant breakthrough in colour occurred. Figure 6 shows a representative treatment train for a textile mill, which includes equalization, coagulation, settling, parallel biochar modules, polishing, and discharge or recycling. The working size example is supported by the EBCT annotations and EBCTs.

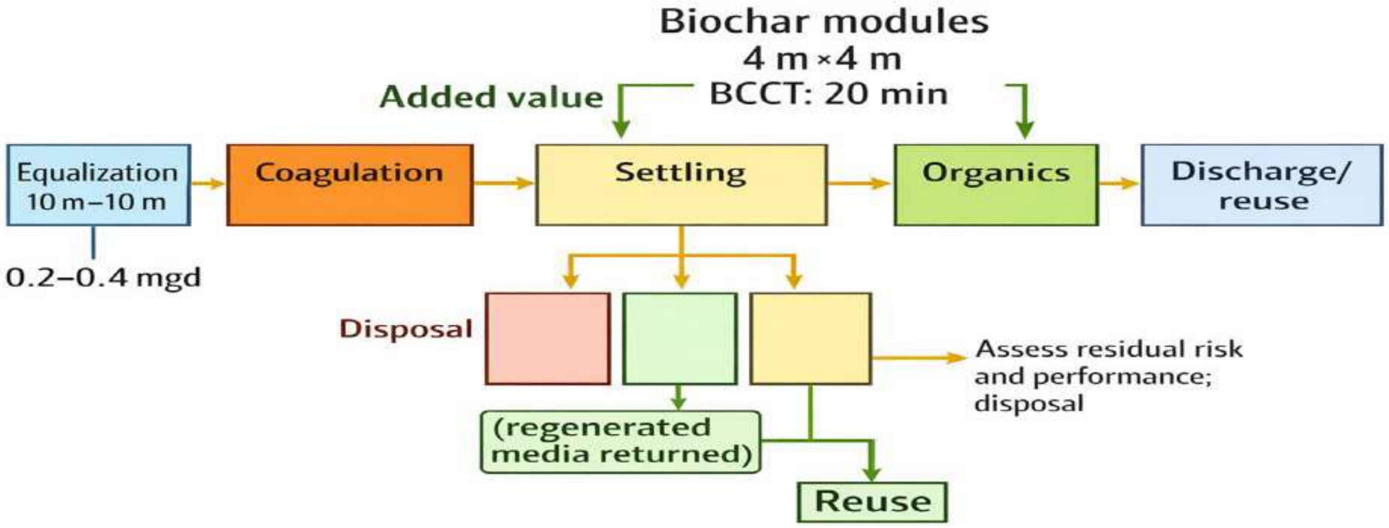


Figure 6
Example process flow diagram for integrating biochar in textile wastewater treatment (Duran-Ros et al., 2023; Eniola & Sizirici, 2023).

4.7.2 Case Study 2: Stormwater Treatment for Metal Removal.

The use of a biochar-amended sand filter in a concrete trough showed 95% removal of dissolved copper and zinc in intermittent flows of 10 m, compared to 70 percent removal in a control sand filter (Patterson et al., 2018). Periodic media samples showed that metals accumulate mainly in the biochar section. The upper layer of the filter was replaced after one year when sediment clogging occurred, and the spent biochar-sand mixture was discarded as a non-hazardous waste. The project showed that biochar can be used in conventional stormwater infrastructure to meet the strict regulatory requirements for metals with little modification to the standard design, except for the blending of biochar. Biochar can be added to green infrastructure to improve performance with little or no additional cost.

4.7.3 Case Study 3: Food Processing Wastewater – Anaerobic Biofilter.

Anaerobic biochar biofilters can be installed in agro-industries to treat high-COD wastewater from agro-industries. For instance, Adesina et al. (Adesina et al., 2025) described a system consisting of a large drum filled with biochar made from coconut husk. Wastewater flowed upward through the drum at a low rate. Biochar provided a surface for the growth of an anaerobic biofilm and also adsorbed the inhibitor, resulting in a higher stability and quality of the effluent compared to the control reactor without biochar, which also included a contact-retrieval step and a cleaning step. 70-80 percent COD removal was observed, and significant pathogens were eliminated within 90 days of running the anaerobic biochar filtration system. The adsorption of the biochar to the toxic spikes and its high surface area promote high-density biomass, which makes it possible to design a compact reactor. No significant biochar attrition was observed mechanically, and no clogging was observed because most of the solids had been deposited in the pre-settlements. This case demonstrates that the route of introduction of biochar filters is not limited to aerobic granular filters but can be introduced in anaerobic systems, packing bed reactors, or even in some designs as a float medium for improved treatment. These case studies demonstrate how biochar biofilters have gone from concept to application. The main determinants in deployment are the low cost of biochar and the ability to tailor it for specified contaminants.

V. CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

It was concluded that the balance between design and hydraulic characteristics influences their performance. In these conditions, biochar filters have repeatedly demonstrated a performance comparable to that of conventional granular media such as sand, anthracite or even granular activated carbon. This flexibility of the design allows biochar filters to be used as a slow filter unit for cleaning and decentralised applications or as a high-speed filter for larger industrial installations. From a hydraulic and operational point of view, biochar beds exhibit favourable properties due to their high porosity and low initial head loss. However, long-term performance depends on appropriate operational strategies, especially the inclusion of backwash capacity for the management of clogging and the maintenance of permeability. Evidence shows that biochar media can effectively be washed with a lower water requirement than conventional media, although pilot tests at the site are still necessary to determine the optimal expansion rate and cleaning frequency. Careful design of the intake and the output channels is also important to ensure uniform flow distribution, minimise channelisation, and reduce mechanical stress on the media.

When produced under suitable pyrolysis conditions like pelletisation, biochar can have high hardness and resistance to degradation comparable to activated carbon. The field and laboratory studies indicate that the loss is progressive rather than sudden and that the operational losses can be managed by routine monitoring and simple containment measures. Therefore, a preference for high-strength biochar is both feasible and appropriate for large-scale industrial applications. Biochar biofilters are effective during the polishing stage of the treatment process. They focus on residual contaminant fractions that persist beyond conventional exposure. They have proven efficient in sectors such as textiles, metalworking, stormwater management, and food processing. This multifunctionality places biochar filters as a valuable addition to the treatment of industrial wastewater. Biochar filters are easier to deploy since they can be retrofitted into existing infrastructure. The remaining obstacles mainly concern standardisation and regulation. Developing recognised specifications for biochar filter media similar to those used for sand or activated carbon would greatly improve quality assurance and regulatory acceptance, thus speeding up the uptake of biochar.

5.2 Recommendations

This review highlighted critical areas for future advancement on the usage of biochar for filtration: The inclusion of predictive models is needed to integrate adsorption, biodegradation, and hydrodynamics in biochar filters to allow for flexible designs. Low-energy recovery technologies like electrochemical and hybrid approaches should be explored to improve the economic performance. Further refinement of the biochar composition through tailored pore structures and surface functionalization should be investigated to target specific industrial pollutants.

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