Chapter 20

Regeneration, recycling, and disposal of spent biochars

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Chapter outline

20.1 Introduction

Among the technologies that are employed to immobilize and degrade both organic and inorganic contaminants in various polluted environmental compartments, biomass-based biochar has been demonstrated to be an effective and environmentally friendly strategy (Crini et al., 2019; Liao et al., 2022; Nguyen et al., 2023; Rasheed et al., 2020; Wang et al., 2020). In addition, biochar has several other advantages, for instance, high-cost efficiency due to the abundance of low-cost feedstock, as well as simplicity of preparation methods (Barquilha & Braga, 2021).

To further improve the biochar pollutant removal efficiency and capture capacity, increasing efforts are currently being carried out to design and develop biochar with improved properties for the immobilization of both organic and inorganic pollutants (Dutt et al., 2020; Liao et al., 2022). However, the main drawback is the management of the spent biochar loaded and concentrated with various pollutants (Hossain et al., 2020). Several technologies are available for the recovery of spent biochar, including filtration, sedimentation, centrifugation, and magnetic separation (Kar et al., 2022). The spent biochar is then either regenerated for reuse or safe disposal via landfilling or incineration (Kozyatnyk et al., 2020), as illustrated in Fig. 20.1.

Regeneration of spent biochar for several other decontamination cycles further lowers the running and operational cost of remediating the contaminated environmental media. In essence, biochar's high recycling and reuse capabilities are fundamental for the economic management of polluted environments (Herath et al., 2021). Therefore, several

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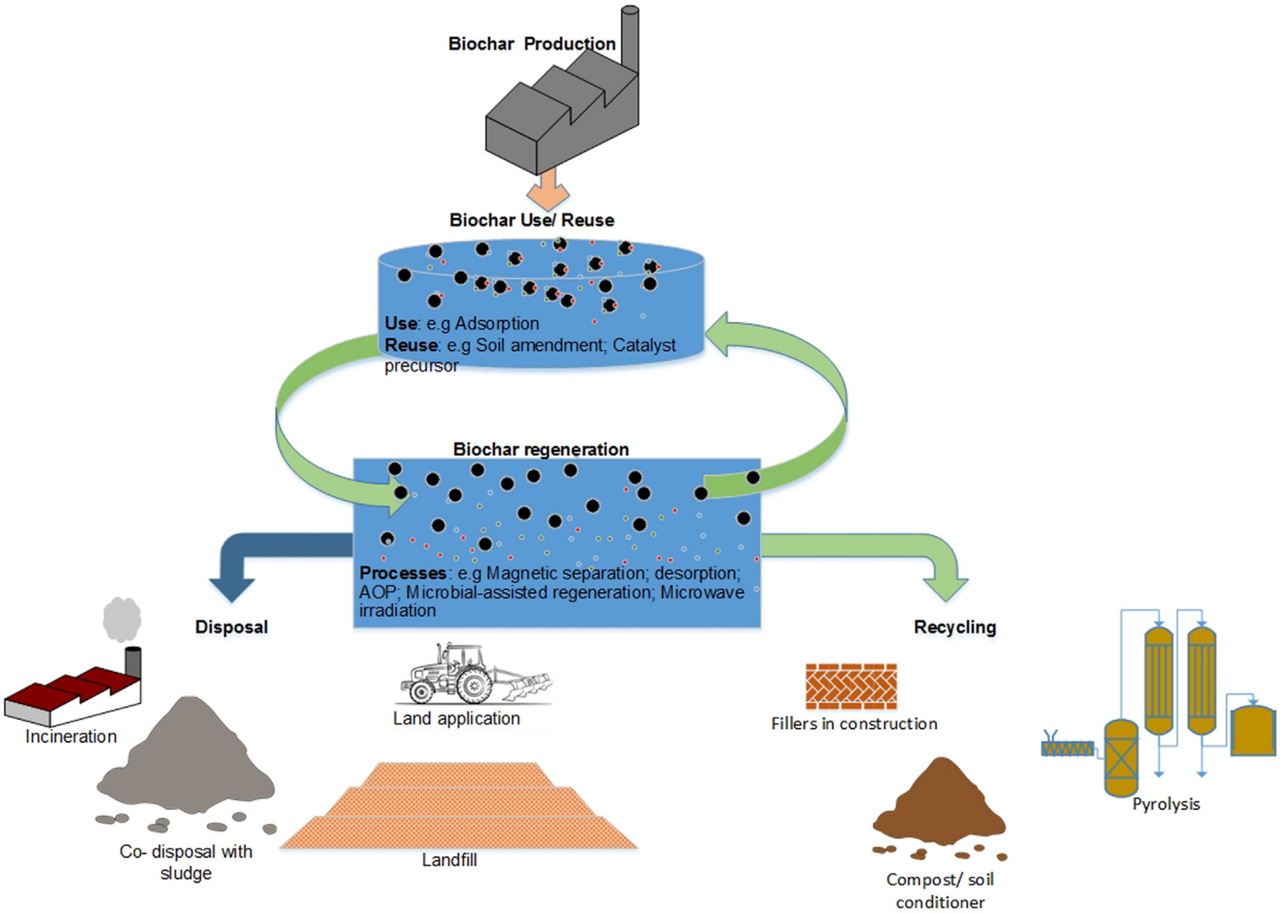

FIGURE 20.1 Reuse, regeneration, recycling, and disposal of spent biochar for a circular economy and environmental sustainability. Biochar used in the process of adsorption can be regenerated and then reused for the same purpose or recycled into other products.

regeneration approaches, such as photodegradation, desorption, and biodegradation of sorbed contaminants, have been proposed, developed, and examined to regenerate and reuse the spent adsorbents (Vakili et al., 2019). The strategies are affected by the type of adsorbent, its properties, and the pollutant type (Alsawy et al., 2022). These approaches can be broadly divided into two main groups (Fig. 20.2), which are the desorption and degradation processes (Omorogie et al., 2016). The degradation/decomposition regeneration process completely depends on mineralizing the adsorbed contaminants and/or converting them into by-products with less toxicity (Liao et al., 2022). This process enables the restoration of the biochar contaminant adsorption capacity.

Ultrasound and oxidation degradation approaches utilize high thermal energy and, as such, are regarded as thermal degradation methods. On the other hand, desorption regeneration techniques employ either themal or nonthermal approaches to break the bonds between the biochar surface and contaminants. Thermal regeneration methods are destructive techniques deployed only if the adsorbate is a waste, and there is no need for its recovery (Sabio et al., 2004). However, because thermal regeneration consumes a lot of energy (temperature up to 800°C), it elevates the process cost, reaching up to 50% of the total cost of producing new biochar (Alsawy et al., 2022). Nonthermal techniques preserve the biochar and can be reused for several other pollutant decontamination cycles (Iamsaard et al., 2022).

Several good reviews are available and have established the potential benefit of biochar application in various environmental media (Barquilha & Braga, 2021; Kah et al., 2021; Kar et al., 2022; Nguyen et al., 2023). Also, the reactivation of spent biochar concentrated with various pollutants for their reutilization has been demonstrated (Hassan et al., 2020). However, a comprehensive analysis and understanding of the mechanisms for the regeneration, as well as possible safe and sustainable management of spent adsorbents loaded with pollutants, are needed. Therefore, this chapter provides a critical summary of the following:

(1) the detailed mechanism and processes for the regeneration of spent biochar;

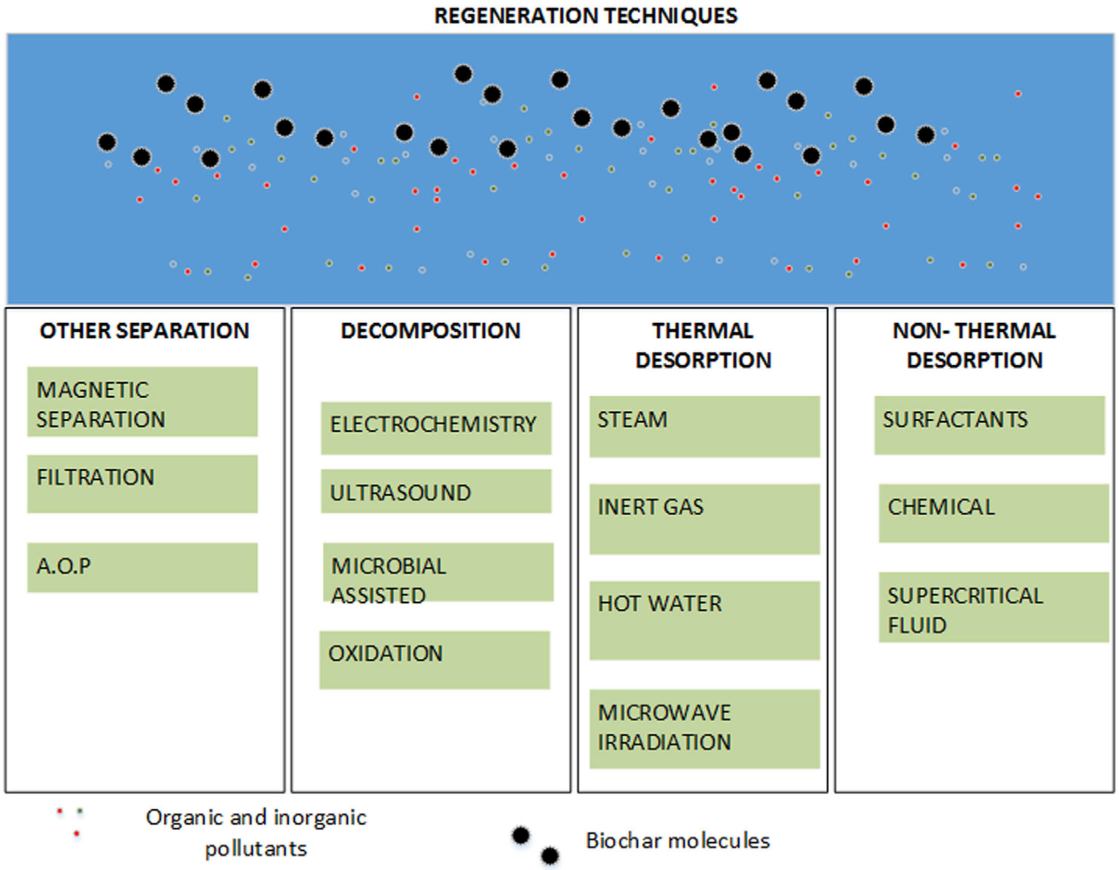

FIGURE 20.2 Different regeneration techniques can be utilized, including separation, decomposition, and degradation (thermal and nonthermal) to recoup biochar.

(2) the recycling and reutilization of spent biochar in various environmental compartments;
(3) the possible safe disposal methods of unrecoverable spent biochar for reutilization; and
(4) challenges and hotspots for future research directions will be discussed.

The findings of this chapter will help readers comprehend the available regeneration techniques and methods for regenerating the adsorbent with minimum capacity loss after several regeneration cycles. Simultaneously, regeneration helps to reduce secondary pollution, while reuse in other processes results in cost-effectiveness and resource recovery.

20.2 Regeneration of spent biochars

Regenerating spent biochar entails reactivating its adsorption and nutrient-retention properties, which may degrade over time or after use. Regeneration is the reverse process of adsorption, which involves adsorbate desorption and adsorbate decomposition (Jia et al., 2016).

From, a good adsorbent should be reusable and recyclable, thereby reducing the cost of purchasing adsorbents. Due to differences in the make-up of the biochar, different regeneration techniques can be used to treat different biochar, as shown in Fig. 20.3. Biochar regeneration efficiencies also vary. For example, in a 2016 study by Shan et al. (2016), the pharmaceuticals that had been adsorbed on spent biochar were degraded by 97% (tetracycline) and 98.4% (carbamazepine). The following section highlights the various regeneration techniques.

20.2.1 Magnetic separation

Depending on the nature of the biochar, magnetic separation can be used as a way of recouping biochar. Adsorbents can be enhanced in terms of specific surface area (SSA), porosity, thermal stability, and other factors by introducing

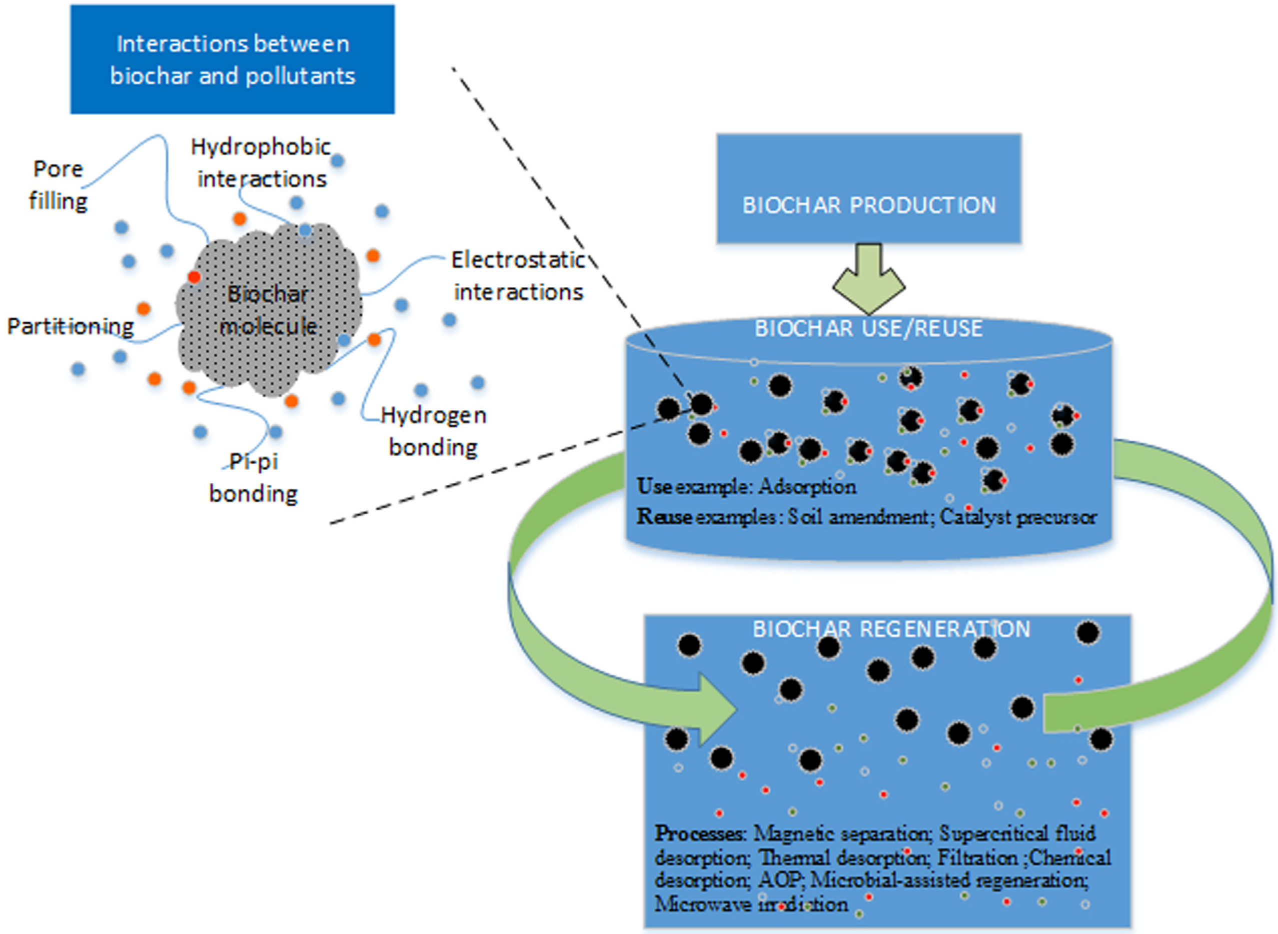

FIGURE 20.3 Schematic illustration showing adsorption and regeneration of adsorbents from wastewater and associated interactions. Adsorption and regeneration of biochar.

metal nanoparticles in the biochar. By so doing, the biochar becomes a magnetic adsorbent. Magnetic biochar has the advantage of improved adsorption efficiency and rate of adsorbent recovery (Gupta et al., 2020). In some cases, biomass substrate is treated with iron (Fe) salts of Fe, such as ferrous chloride, ferrous sulfate, and ferric chloride, are used to make magnetic biochar. Such biochar can be easily regenerated by magnetic separation (Li et al., 2016).

Interestingly, biochar loaded with iron can be pyrolyzed directly to produce magnetic biochar (Ren et al., 2018) and be reused. Such spent magnetic biochar is separated by applying an external magnetic field. These have been mostly used on a laboratory scale (Ren et al., 2018).

20.2.2 Filtration

Filtration as a method of biochar regeneration depends on the particle size of the biochar. The larger the adsorbent particle size, the easier it is to separate. Nowadays, membranes are commonly used for filtration separation, with their recyclability and separation efficiency dependent on the ability of the biochar to disperse. In membrane bioreactors, biochar has the potential to reduce membrane fouling, thereby increasing the design lifespan of the biomembrane (Tan et al., 2016). However, the downside of filtration is that most membranes cannot remove nano-sized biochar. Additionally, filter media often needs to be backwashed.

20.2.3 Thermal desorption and decomposition

Thermal regeneration is another effective method of biochar regeneration. Heat or high temperatures are used on the spent biochar in a controlled environment to remove adsorbed contaminants and restore its surface properties. This process is similar to the initial pyrolysis used to create biochar. Thermal regeneration involves applying heat to biochar to disturb the physical and chemical bonding between biochar and pollutants (Momina et al., 2018). This technique is currently being used at industrial and commercial levels for the regeneration of activated carbon. Heat application to biochar in aerobic conditions at temperatures below 500°C will eliminate the carbon matrix and its volatile compounds (Zhang et al., 2020).

However, conditions for thermal treatment may differ or be subject to the following factors:

- Type of adsorbents
- Contaminants
- Purpose of subsequent use

These conditions require further research and improvement to make the process scalable (Kar et al., 2022).

20.2.4 Chemical desorption

Solvent regeneration mainly applies to high-concentration and low-boiling-point organic matter adsorbents (Zhang et al., 2021). Solvent regeneration uses the equilibrium relationship between biochar, solvent, and adsorbate to break equilibrium by altering the temperature and pH of the solvent so as to necessitate the regeneration process of pollutants from the biochar. Acids and alkali/base compounds that are usable as solvents in the regeneration process are H_2SO_4, HNO_3, HCl, EDTA (ethylene diamine tetra-acetic acid), NaOH, $Ca(NO_3)_2$, and $NaNO_3$(Gupta et al., 2020; Yang et al., 2020). Low pH has been seen to promote desorption, using acids such as H_2SO_4, HNO_3, and HCl as solvents (Gupta et al., 2020). However, very acidic environments have a tendency to deform or destroy the structure of the adsorbents, thereby decreasing the adsorption capacity when reused. As such, treatment using strong acids requires the biochar to be steady in its mechanical structure. Chelators such as EDTA can also be added to improve the rate of desorption. Within their structure, chelators have several functional groups, such as carboxyl (CO-OH) and amine groups, that attract pollutants to form complexes.

20.2.5 Supercritical fluid desorption

Supercritical fluids (SCFs) are used to extract or separate using differences in operating pressure. Momina et al. (2018) defined SCFs as fluids that are formed when a substance is heated to temperatures that are beyond its critical temperature and compressed above its critical pressure. Regeneration using SCFs allows for a short operating cycle, low operating temperature, and reduced biochar loss. Additionally, this technique can recover adsorbate without altering much on the physicochemical properties of the biochar. On the downside, supercritical desorption has high-pressure resistance and high equipment cost. The SCFs are thought to be better substitutes to replace incineration and chemical solvents (Efaq et al., 2015). The most common being CO_2 because CO_2 is not combustible, very economical, and nonhazardous (Noman et al., 2020). CO_2 has reduced surface tension and a high mass transfer rate. This process, however, requires more innovative approaches so that the cost is reduced and is also applicable on an industrial scale level. On the contrary, CO_2 has a lower regeneration capacity for phenol-loaded adsorbents. However, if supercritical water is used in place of supercritical CO_2, there was 100% desorption efficiency achieved on the same phenol-loaded adsorbents (Salvador et al., 2013). Supercritical water can be efficient in some cases, while it needs to be aided with other catalysts such as H_2O_2 and alkali metal in other cases. The use of supercritical water as the SCF entails reduced process duration and lower process cost. However, it requires high pressure. The high-pressure constraint makes its process cost higher, as well as reduces its applicability at the industrial and commercial levels. Therefore, supercritical water regeneration can only be applied on a small scale. In soils, the SCF assists the process of desorption as a typical solvent. The adsorbate is further condensed and collected in a separate small container.

20.2.6 Advanced oxidation processes

In recent years, much acknowledgment has been given to the use of advanced oxidation processes (AOPs) as a technique applicable to spent biochar regeneration (Acevedo-García et al., 2020; Fdez-Sanromán et al., 2020). Studies have shown AOPs to be usable in the regeneration of spent biochar (Acevedo-García et al., 2020), such as coffee biochar. In other studies, viable regeneration by various AOP techniques, including electro-Fenton reaction and Fenton reaction with hydrogen peroxide (H_2O_2), has been successful.

20.2.7 Microbial-assisted regeneration

Microbial-assisted biochar regeneration involves regenerating the adsorbent via microbial action or degrading of biodegradable adsorbates on the biochar surface (Abromaitis et al., 2016). This procedure makes use of either a pure culture or a mixed culture of microbes, such as fungi, bacteria, and even algae. The microbes are allowed to mix in batches, or alternatively, it is done in wastewater treatment during biological treatment of wastewater (Momina et al., 2018). Due to the nature of microbes, the adsorbent surface needs to be nontoxic and conducive to the growth and habitation of the microbes (Baskar, 2017).

Bioregeneration of spent sorbents can be done in two ways:

1. By desorption following a concentration gradient, where the microbes act on or degrade the unconfined organic material, thereby decreasing the amount of the impurities in the aqueous phase. The concentration gradient is set between the biochar surface and the aqueous media (Klimenko et al., 2002).
2. By the action of extracellular enzymes released by microbes, the pollutants are degraded as they diffuse into the porous structure of the biochar, degrade and hydrolyze the trapped pollutants.

The whole procedure is dependent on other aspects, such as microbial diversity, generation time, the microorganism-pollutant concentration ratio, nutrient availability, temperature, and dissolved oxygen level (Klimenko et al., 2003). These can be optimization factors depending on the needs and nature of the microbes.

20.2.8 Microwave irradiation regeneration

This technique utilizes microwave energy to heat the biochar molecules. Desorption takes place due to the rapidness, selectivity, and controlled heating of the adsorbent molecules (Falciglia et al., 2018). Microwave treatment evenly heats the biochar from the outer surface to the inside the core. Microwaves did not change the pores in the biochar molecules; hence, the properties of the adsorbent were preserved during regeneration, unlike with conventional thermal heating. Though the microwave irradiation procedure shows more temperature control, the technique can be costly at an industrial scale. The setup costs, as well as energy requirements, make the technique not very sustainable and uneconomic; hence, it requires more research to make it economically viable (Gagliano et al., 2020).

20.3 Reuse, recycling, and disposal of spent biochar for a circular economy and environmental sustainability

Biochar is a carbonaceous material attained from organic wastes by carbonization under an inert atmosphere (Andrade et al., 2020). After being used for a specific purpose and when no longer needed, spent biochar has to be recycled or disposed of in an environmentally friendly manner (Kar et al., 2022). However, in a bid to promote a circular economy, spent biochar has been utilized in different applications such as soil conditioning. However, recycling and disposal of spent biochar depend on its quality and potential contaminants, which are considerably influenced by the feedstocks, pyrolysis conditions, and pyrolysis technologies (Zahed et al., 2021). In addition, as highlighted by Tan et al. (2016), factors such as stability, potential secondary pollution, effect on carbon sequestration, and economic feasibility have to be considered in the recycling or disposal of spent biochar. Nonetheless, there are several recycling and disposal options for spent biochar, which include using it in heavy metal adsorption, soil amendment, composites, energy storage, tissue engineering, and ammonium adsorption in water, among others. When utilizing the spent biochar, care needs to be taken to ensure that the adverse effects of pollutants are minimized and controlled.

20.3.1 Reuse as a soil amendment

If the spent biochar is free from contaminants and still retains beneficial properties, it can be reused as a soil amendment. Mixing it into garden beds, agricultural fields, or compost piles can improve soil health and fertility. In an experiment, He et al. (2022) utilized spent biochar from the textiles industry as a precursor for compost generation in a process that was conducted using dye-loaded spent biochar, ready compost made of vegetable waste, and sawdust. They concluded that the obtained compost can be used as a soil conditioner for enhancing plant growth. The same conclusions were made by Ramrakhiani et al. (2022), who researched the likelihood of using the spent Zn(II)-laden biochar in the making of plant microfertilizer and soil-fertility improvers. They discovered that the application of the Zn(II)-laden biochar mixed with soil achieved an optimistic germination on the seeds of *Cicer arietinum*, growth parameters of plants, as well as content of protein and chlorophyll a and b. Using spent grain biochar on Hop (*Humulus lupulus L*), Amoriello et al. (2020) noted that biochar significantly improved root growth, and the addition of biochar to the soil further improved yield in terms of the number of cones on the plants. Apart from improving soil nutrient content, spent biochar can also improve soil water retention capacity and drainage (He et al., 2022; Wang et al., 2016). Similarly, Şeker & Manirakiza (2020) concluded that compost and biochar significantly improved aggregation and water retention characteristics of sandy clay loam soil. Therefore, biochar acts as a soil conditioner, improving physical, chemical, and biological properties and enhancing soil fertility and crop yield (Tsolis & Barouchas, 2023), which presents an opportunity for it to be reused as a soil amendment.

20.3.2 Composting

Spent biochar can be added to compost piles as a carbon-rich component that helps balance the carbon-to-nitrogen ratio, improves aeration, and acts as a stable organic matter in the aerobic composting process (Agyarko-Mintah et al., 2017; Liu et al., 2020). Biochar makes organic waste harmless and stable and plays a role in suppressing carbon and nitrogen losses (Liu et al., 2020). This allows the biochar to enhance the quality of the resulting compost. Zhang et al. (2020) noted that straw biochar hastens organic matter degradation and produces nutrient-rich compost, the addition of biochar with the optimal concentration of 10%−15% resulted in more mature and humified, with a decrease in dissolved organic carbon content and NH_4 concentration compared to the control. The concentrations of water-soluble nutrients, including PO_4^{3-}, K, and Ca^{2+}, were also increased with biochar addition. The addition of biochar in composting can reduce the emissions of CO_2, N_2O, and other gases during composting (Li et al., 2016; Liu et al., 2017).

20.3.3 Land application

In some cases, spent biochar can be safely applied to nonagricultural land, such as land reclamation projects or landscaping. Research has shown that spent biochar can be used in land reclamation because of its soil improvement and heavy metals sequestration abilities (Raclavská et al., 2021). The application of biochar in contaminated matrices can also help mitigate the damage caused by agrochemicals and improve crop quality. Additionally, the addition of biochar to composting processes has been shown to reduce volatile organic compound emissions and accelerate the biodegradation process. Biochar can also be used as a stand-alone amendment or in combination with biosolids to enhance tree growth and root development. An assessment of the potential of using an acacia-biochar system for spent mine site rehabilitation by Reverchon et al. (2015) provides insights into the potential benefits of using biochar for mine site rehabilitation. The use of spent biochar in land reclamation can contribute to sustainable agriculture, soil improvement, and environmental remediation. However, it is important to ensure that the biochar is free from contaminants and does not pose any environmental risks.

20.3.4 Regeneration through pyrolysis

Spent biochar can be recycled and regenerated through pyrolysis again. A study by Cui et al. (2022) revealed that pyrolysis of spent biochar can be used to regenerate valuable biochar from exhausted hydrochar sorbent. In addition to increasing the functionality of the biochar, in cases where the biochar was used as an adsorbent, recycling of spent biochar can also immobilize heavy metals such as cadmium (Fan et al., 2023). However, as noted by Tan et al. (2023), regenerating and recycling spent biochar depend on the scale and available technology, with the integration of continuous reactors and catalysis being more efficient and economical for commercialization. As noted in a study by Vercruysse et al. (2021), the regeneration of spent biochar can be done by mixing it with fresh biomass and pyrolyzing it again using slow pyrolysis at different temperatures. Spent biochar can also be used as a feedstock for renewable energy production or converted into bio-oil or syngas (Lee et al., 2020). Therefore, depending on the available technology and type of feedstock, spent biochar can be regenerated through pyrolysis.

20.3.5 Contaminant removal and landfill disposal

If spent biochar contains harmful contaminants, it might need specific treatment to remove or mitigate them. Usually, spent biochar is disposed of after the recovery of heavy metals or immediately after the adsorption process; in both situations, there may be secondary pollution from used biochar and the chemicals used to prepare the biochar (Gupta et al., 2020). Hence, the disposal of spent biomaterials contaminated with harmful organic ions also poses social and environmental problems. It may be necessary to dispose of the biochar in a designated landfill or waste management facility capable of handling contaminated materials. The spent adsorbents can be safely disposed of in landfilling (Kozyatnyk et al., 2020). However, in some cases, pretreatment of the biochar will be necessary before landfilling is done. For example, disposal of peat-based biochar, which is used in the removal of heavy metals, would require pretreatment (Kar et al., 2022). The downside of landfilling spent biochar appears in landfills where it is susceptible to metal-leaching and dispersion (Jambeck et al., 2007). Hence, it may be necessary to dispose of the biochar in a designated landfill or waste management facility capable of handling contaminated materials. Landfilling can be a viable option for final management of biochar. However, it is important for one to determine the concentration of the contaminant before disposing.

20.3.6 Incineration

Spent biochar can be incinerated as a final management technique (Fernández-González et al., 2019). Because biosorbents are rich in biomolecules such as lignin and cellulose, incineration not only greatly reduces the mass and volume of waste biomass but also recovers heavy metals and thermal energy (Ronda et al., 2016). However, this presents problems such as air pollution, which could potentially harm humans and the environment (Hu et al., 2022). Chaukura et al. (2016) suggested other disposal options because incineration will cause more pollution by emitting greenhouse gases (GHGs). Spent biochar can be used to make other products, such as activated carbon, which appears to be a new, potentially cost-effective, and environmentally friendly carbon material with great application prospects in many fields such as water purification (Tan et al., 2016). Activated carbon is produced from any carbon source (fossil, waste, or renewable) and is engineered to be used as a sorbent to remove contaminants from both gases and liquids (Marsh & Rodríguez-Reinoso, 2006; Mukherjee et al., 2022). Spent biochar has been observed to have reduced nitrogen, sulfur, and oxygen while having high carbon levels. These characteristics make spent biochar a good alternative to coal, as it has a high calorific value while at the same time producing less of the toxic emissions and corrosiveness (Kar et al., 2022). Spent biochar can be used to make other products, such as activated carbon, which is used in water purification and other applications.

20.3.7 Fillers in novel construction materials

The cement industry contributes 5%−8% of the GHG emissions (Miller et al., 2021) due to its energy-intensive processes. As such, any alternatives or substitutes to cement in the construction industry are sought-after. Spent biochar has been used in making construction bricks as a geopolymer. Using it as a geopolymer has additional environmental benefits such as decreasing natural resource depletion such as clay, and also the ability to capture GHGs, including CO_2 and CH_4, in its solid phase as carbon. When compared to concrete bricks, biochar bricks (composed of cement, plastic, and biochar) had competitive qualities in terms of compressive strength, insulation, water absorption, and hardness (Nithyalakshmi et al., 2022).

20.3.8 Catalyst precursors for trace metal-rich spent biochars

The physicochemical properties of biochar can be improved through various processes in order to give them properties of catalysts or catalyst supports. This has been attributed to the various surface functional groups present, in addition to their large surface area. Despite all these properties and positive factors, the ability of spent biochar as a catalyst, especially for advanced electrocatalytic processes, hence more study is required in this regard (Ramos et al., 2022).

20.3.9 Incorporation in solid fuels

Biochar can be incorporated into solid fuels for use in different applications (Gwenzi et al., 2021). The biochar has fuel properties with calorific values ranging from 24.12 to 26.24MJ/kg (Vukićević et al., 2024), which was way higher than that of wood (12.5MJ/kg). Ash content of biochar varies depending on the source of the waste charred. Various studies showed different ash values, for example, agricultural waste biochar was found to be in the range of 12%−20% (Vukićević et al., 2024), which was within the range of solid fuels, sawdust was in the range of 0.65%−1.7% and that of sewage sludge was as high as 45.7% (Pulka et al., 2016).

20.3.10 Codisposal of sludge

In various researches, biochar has been mixed with sewage sludge. Its addition even in small quantities proved to yield some benefits such as increased pile temperature and also aid ammonium transformation to nitrite, thereby reducing the total nitrogen losses (Liu et al., 2017). Furthermore, the application of biochar mixed with sludge can help reduce soil contaminants such as polycyclic aromatic hydrocarbons (Stefaniuk et al., 2017) and hence the mixture can be used for different environmental remediation applications, especially involving organic pollutants (Chen et al., 2020).

20.4 Behavior and fate of contaminants in spent biochar

Due to aging and several recycling cycles of the biochar, its chemistry, including the surface functional groups, can be distorted through oxidation or microbial degradation activities (Downie et al., 2009; Khorram et al., 2016). It is also noted that the adsorption capacity of biochar decreases with time as a result of the aging process aided by the clogging of biochar pore space with soil particles and the removal of reactive biochar surfaces due to reduced inactivity by soil mineral elements (Pignatello et al., 2006). This compromises the biochar's capacity as a pollutant removal agent, causing the accumulation of pollutants impacting environmental health and the ecosystem. Additionally, studies have indicated the reversible pesticide adsorption in soils amended with recycled biochar samples through various ways, including sorbent swelling during adsorption process and penetration of the pesticides via active diffusion (George, 2022). This enhances the diameter expansion of the micropores, which could result in the micropore network deformation (Bahia, 2022; George, 2022), and the weak binding between the applied pesticides and spent biochar components (Khorram et al., 2015; Tatarková et al., 2013).

The sorption capacity of biochar particles in amended soils deteriorates on herbicides due to aging (Maestrini et al., 2014; Obia et al., 2017; Mendes et al., 2018). This is attributed to structural changes (Mendes et al., 2018) such as reduced SSA and the porosity of the aging biochar, resulting in the blockage of micropores and the sorption sites, further increasing the bioavailability of contaminants in the environment (Yavari et al., 2015). Other studies reported a reduction in the sorption capacity of diuron by approximately 47%−68% against the control soil, which could be due to the clogging of the pores of the soil particles with spent biocha allowing for the bioaccumulation of the pollutant (Martin et al., 2012). A loss in spent biochar's mass has been revealed over time (Maestrini et al., 2014; Obia et al., 2017), however, Dong et al. (2017) reported an approximated loss of about 40% of biochar in 5 years irrespective of the applied mass during the amendment cycle (30, 60, or 90 t/ha[1]). This, however, threatens environmental health as the cumulative effect of contaminants could reach unprecedented levels with the loss of biochar, which significantly plays a pivotal role in immobilizing contaminants in the soil and water ecosystems. Further, studies revealed that structural and chemical changes that transform the biochars' sorptive capacity depend on the type of each material, the pyrolysis temperature, conditions, and the time at which the material will be incubated in the soil, as some mineral elements were observed to have filled pores at the expense of contaminants (Trigo et al., 2014). The spent biochar macropores, which previously served as a route for adsorbate exposure locking up contaminants, may become degraded by selected plants for phytoremediation, whilst providing nutrients to microbes mimicking microbial activity for the degradation of contaminants (Yang et al., 2010).

In order to maintain pesticides and herbicides pollutant concentrations within tolerable limits that do not cause severe environmental health loss following the aging of spent biochars in amended soils, bioremediation processes involving hydrolysis, conjugation, and degradation could be a panacea in providing frugal solutions to the rising levels of contaminants in soil and water (Yang et al., 2010). The enzymatic degradation exhibited by microorganisms, however, requires an understanding of the pollutant's chemical and structural composition, and additionally, the molecular factors that can affect pollutant transformation to a lesser toxic and/or its complete removal from the environment (Mali et al., 2023). The increased regeneration cycles of spent biochar could result in the decline of their adsorption capacity, through the erosion of their mechanical and chemical stability. These functional declines would compromise their capability as contaminants remediation matrices both in soil and water, negatively impacting the environmental health and well-being of humans as contaminants would bioaccumulate in food webs (Gwenzi et al., 2017).

Above all, some disposal techniques of spent biochar and other adsorbents are either desorption by acid and base treatment or landfilling techniques (Gupta & Babu, 2009; Wang et al., 2015). However, the disposal and/or dumping of the spent biochar threaten environmental health as possibilities of leaching, explosions, stinking, and volatilization of unwanted pollutants may occur (Ruaa et al., 2021; Vakili et al., 2019). Due to the affinity for active sites on the adsorbents, the desorption process meant to determine the fate of pollutants usually poses challenges making it not economically viable to use other adsorbents, as they are rendered useless and regarded as secondary waste (Ruaa et al., 2021). Recycled spent biochar also finds its way under the resource utilization strategy on which they can be transformed into valuable electroactive materials (Chen et al., 2021; Sundriyal et al., 2021), and also can be utilized in construction (Selvasembian et al., 2023).

Transitional metals (Cu, Fe, Co, Mn, and Ni) are mostly found as a nuisance in soil and water contamination, however, they can be utilized in designing cost-effective catalysts for the energy-related oxygen evolution reaction (OER), which is essential in the development of green hydrogen technologies (Suen et al., 2017; Zhou et al., 2021). The development and advancement in green hydrogen energy are seen as a panacea and enhanced strategy in the production of efficient, cheap, and sustainable OER electrocatalysts (Wan et al., 2021), while consuming spent biochars, which are likely to contaminate the environment due to their capacity to contain pollutant residues (metal-laden). As such technologies, including the integration of the electrocatalytic transition metal borides with the porous and large SSA spent biochar producing heterostructured electrocatalysts provides both an economic and environmentally based benefit (Chen et al., 2021; Mao et al., 2020). This is also termed the bidding strategy on which the waste is converted to wealth. This is attributed to the increased performance of the electrocatalysts and the removal of pollutant-bound spent biochar from the environment.

Studies have also pointed to the use of recycled Cr-adsorbents as catalysts for the removal of ulfur-containing volatile organic compounds, which is the methyl mercaptan (CH_3SH), as an alternative way of determining the fate of pollutants on spent adsorbents compared to the conventional landfilling and desorption using acid/base treatment (He et al., 2018). Srivatsav et al. (2020) reiterate that biochar's capacity to adsorb pollutants deteriorates when subjected to multiple operational cycles. Due to the high regeneration cost of spent biochar, disposal challenges of metal-laden and other bound pollutants could be hazardous to the environment due to volatilization and pungent smells (Srivatsav et al., 2020). At high temperatures ($>400°C$), heavy metals bound on spent biochar tend to volatilize and contaminant the immediate environment through metal pollution (Lehmann & Joseph, 2009). This is also further supported by the fact that biochars are recalcitrant forms of organic material, therefore, their decomposition can be increased by a further 10°C rise in temperature, compromising their capacity as GHG sequestration media (Davidson & Janssens, 2006; Lehmann & Joseph, 2009). Spent biochar loses weight over multiple regeneration cycles and mineralization could also exacerbate leaching, eluviation, and erosion, resulting in the spread of pollutants due to offsite deposition and lateral export across the drainage pattern (Dong et al., 2017; Lehmann & Joseph, 2009; Rumpel et al., 2006). Through deposition, spent biochar could be buried under both oxygen-free or inert conditions, and this will likely increase underground contamination if metals and other pollutants are desorbed from the biochar. Due to a plethora of impacts on the environment posed by spent biochars at the end of their cycle, they can also be utilized as biocarriers (Srivatsav et al., 2020). Overall, it is worth noting that establishing the relationships between biochar properties and the exposed environmental conditions (e.g., climate and soils) could be fundamental in estimating their stability vis-à-vis decomposition rates, which largely occur over annual to hundreds of years disposing pollutants into the environment.

20.5 Summary and future research directions

Biochar has been demonstrated to be effective in the capture and removal of both organic and inorganic contaminants, as it is widely applied in various environmental media. The spent biochars generally pose a major drawback in the circular economy of the utilization of biochars. However, the spent biochar can be regenerated using techniques such as AOPs, filtration, and chemical and thermal desorption. The current regeneration approaches are dependent on the type of feedstock used for biochar preparation, and contaminant type. Recently, there has been increasing development of advanced biochar with improved contaminant capture capacity and removal efficiency in various environmental compartments. The disposal of spent biochar loaded with contaminants is a major challenge. The spent biochar can be regenerated/activated for reuse as soil amendments, composting, and general land reclamation. If the spent biochar cannot be regenerated, it can be safely disposed of via landfilling or incineration. The reuse of the spent biochar has environmental benefits, as well as reduces the overall cost of the application.

Although the reuse of spent biochar has some environmental benefits, the challenge of secondary pollution is not yet clear, and this aspect is poorly studied relative to biochar applications in remediation. Also, when they are incinerated, the possibility of producing some toxic air pollutants is not clear. Therefore, researchers need to put effort into investigating the effect of incinerating spent biochar on the production of toxic air pollutants. Besides, when landfilled, the possible effects of leaching and polluting underground water need to be further examined.

Owing to the current emphasis on attaining minimum levels of waste generation, circular economy, and enhanced resource efficiency in a bid to achieve environmental sustainability, the following areas could also be pursued for research and improve removal of contaminants using biochar in various environmental media:

- Development of resource-oriented technologies for the reclamation of impurities from spent adsorbents.
- Studies examining the possibilities of groundwater contamination due to long-term leaching of contaminants from spent biochar disposed of in landfills.

- Long-term kinetic studies on the worthiness of recycling spent biochar as a source of nutrients.
- Long-term studies on the stability of reusing and recycling of spent adsorbents.
- Transformation of spent biochar into value-added products for recycling and reuse.
- Studies on the toxicity of adsorbents before their reuse in other applications.
- Regeneration techniques that are energy-efficient for spent adsorbents.
- Identifying new reuse applications for the management of spent adsorbents.
- Life-cycle analysis and risk assessment of recycling and reuse of spent adsorbents.

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