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Uso do biochar na sorção de contaminantes e restauração de solos degradados: uma revisão sistemática

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R E S U M O

O biochar é um produto de biomassa submetido ao processo de pirólise, sob altas temperaturas e ausência de oxigênio. É um material que dispõe de uma produção de baixo custo e com vastas opções de aplicabilidade, entre as mais exploradas estão: recuperação de solos degradados pelas atividades agropecuárias e sorção de contaminantes através da biorremediação de áreas poluídas. Deste modo, este material objetiva demonstrar a produção e caracterização do biocarvão, e discutir suas aplicações para melhoramento de solos e redução da concentração de substâncias tóxicas e nocivas, como corantes têxteis e metais pesados, descartados indevidamente no meio ambiente, tudo isso a partir da seleção de referências relevantes que abordam de modo claro e consistente a aplicação do biochar e seus efeitos. A partir dos trabalhos analisados constatou-se que o biochar exerce um alto poder de sorção de uma variedade de poluentes emergentes, como: fármacos, pesticidas, corantes têxteis e metais pesados, retendo, em algumas aplicações, até 90% da concentração original do contaminante. Além disso, o biocarvão é uma das principais alternativas para recuperação de solos explorados por longos períodos como áreas de cultivo ou de pastagens, obtendo, para a grande maioria das aplicações do biochar a melhoria das propriedades do solo, como: pH, retenção de nutrientes e teor de carbono. Portanto, o biochar é um material carbonáceo com alta viabilidade produtiva e grande eficiência nos processos de biorremediação e recuperação de áreas degradadas.

Palavras-chave: biocarvão, biorremediação, efluentes têxteis, metais pesados, teor de carbono.

Use of biochar in contaminant sorption and restoration of degraded soils: a systematic review

A B S T R A C T

Biochar is a biomass product submitted to the pyrolysis process, under high temperatures and absence of oxygen. It is a material that has a low cost production and vast options of applicability, among the most explored are: recovery of soils degraded by agricultural activities and sorption of contaminants through the bioremediation of polluted areas. Thus, this material aims to demonstrate the production and characterization of biochar, and discuss its applications for soil improvement and reduction of the concentration of toxic and harmful substances, such as textile dyes and heavy metals, improperly disposed of in the environment, all this from the selection of relevant references that address clearly and consistently the application of biochar and its effects. From the analyzed works it was found that biochar exerts a high sorption power of a variety of emerging pollutants, such as: pharmaceuticals, pesticides, textile dyes and heavy metals, retaining, in some applications, up to 90% of the original concentration of the contaminant. Furthermore, biochar is one of the main alternatives for the recovery of soils exploited for long periods as cultivated or pasture areas, obtaining, for the vast majority of biochar applications, the improvement of soil properties, such as: pH, nutrient retention and carbon content. Therefore, biochar is a carbonaceous material with high productive viability and great efficiency in bioremediation processes and recovery of degraded areas.

Keywords: biocarcoal, bioremediation, textile effluents, heavy metals, carbon content.

Introduction

Environmental pollution arises from various factors, including agriculture, livestock farming, improper disposal of waste, and untreated industrial effluents (Barros et al., 2021; Guimarães et al., 2022; Costa et al., 2023). These activities necessitate subsequent remediation, which involves addressing contaminants and restoring soil properties among the intervention measures.

Much of the treatment methods for highly toxic compounds involve complex processes, costly technologies, and materials, which has prompted the search for economically and environmentally viable alternative solutions (Bayouli et al., 2021; Saravanan e Kumar, 2022). In agriculture, the use of fertilizers has become essential as soils lose their nutritional capacity and the demand for high-resistance and fast-growing crops intensifies. In this regard, among the technologies gaining prominence in effluent treatment and soil correction and enhancement are biochars. These materials involve lower-cost and more effective adsorption processes and can also be applied to improve degraded soils (Assirey e Altamini, 2023).

The creation of biochar arose from the need to enhance the properties observed in natural biomasses during small-scale contaminant treatment processes through adsorption. Characteristics such as porosity, specific surface area, and cation exchange capacity limited the usability and application of biomasses to various types of contaminants. These properties could be readily expanded by transforming these materials into biochar through controlled burning processes (Pang et al., 2021).

According to Assirey and Altamini (2023), biochar can be defined as a product resulting from the thermochemical conversion of biomass, produced under high temperatures and limited oxygen presence. It is a material whose raw material can be easily obtained, considering the diversity of organic residues, whether agricultural or forestry in origin, or even waste materials, which can be used in its production.

In broad terms, biochar can be described as a solid and environmentally friendly material. It involves a low cost in terms of raw materials and production processes, has a wide availability, and exhibits characteristics such as mechanical and thermal stability. Moreover, it shows a high affinity for removing both inorganic and organic contaminants, surpassing the efficiency of commercial activated charcoal (Assirey e Altamini, 2023; Safarian, 2023).

Biochar has been widely recognized in the scientific community due to its increasing use across various environmental applications. Its configurations and sources of origin contribute to enhanced properties, such as a high carbon content, elevated specific surface area, and a strong capacity for cation/anion exchange. Several studies indicate that biochar can effectively eliminate pathogenic organisms, inorganic elements like heavy metals, and organic contaminants such as dyes through adsorption/desorption processes (Han et al., 2021; Haider et al., 2022; Murtaza et al., 2022; Galaburda et al., 2023; Safarian, 2023).

According to Zhao et al. (2021), Isaac and Siddiqui (2022), Perveen et al. (2022), and Assirey and Altamini (2023), the use of carbonaceous materials and adsorptive processes in treating effluents has garnered increased attention due to characteristics such as high performance, improved cost-effectiveness, ease of production and implementation, accessibility and diversity of raw materials, regenerative capacity, and environmental and ecological significance.

In addition to conventional adsorption mechanisms involving biochar, other reactions such as electrostatic interaction, pore filling, and precipitation are observed through the interaction of these materials with contaminants, favoring the diversity of contaminating substances they can be applied to, including emerging contaminants.

According to Isaac and Siddiqui (2022), far beyond the employability of biochar in remediating pollutants, this material also boasts a vast scientific history focused on investigations involving the enhancement of soil agricultural performance, waste management, mitigation of effects resulting from climate change, production of biofuels, and remediation of organic, inorganic, and microbial components that compromise the quality of water resources.

However, there are still gaps to be explored regarding its application for treating different types of effluents and optimizing its adsorptive characteristics to enhance its efficacy in agricultural settings (Pinnamaneni et al., 2023). Furthermore, the need for investigation into the feasibility of large-scale production, as well as the assessment of environmental safety and potential adverse interactions with soil and organisms within environmental ecosystems, before considering its widespread adoption as a solution for environmental pollution, emerges as impactful aspects requiring detailed analysis for its utilization across various fields.

In light of this, this systematic review aims to analyze, through a thorough examination of articles, the production and characterization of various types of biochars and discuss the efficiency aspects of this material in different environmental processes.

This study aims to assess the efficiency potential displayed by different types of biochars in improving unproductive soils and in the bioremediation of industrial and agricultural contaminants that are potentially toxic to the environment.

Materials and Methods

This scientific article employs a bibliographic review methodology to compile and analyze studies published between 2021 and 2023 related to the use of biochar as an adsorbent material in wastewater treatment.

The search was conducted in scientific databases such as PubMed, Scopus, and Web of Science, using relevant keywords such as "biochar," "adsorption," "wastewater treatment," "contaminants," among others. Articles in both English and Portuguese were included, addressing aspects of biochar's efficiency in removing organic and inorganic contaminants, its application in various types of effluents, as well as studies reporting its environmental implications and the economic viability of large-scale production.

The selected articles underwent a critical and comparative analysis aiming to identify trends, knowledge gaps, and future research directions related to the topic. The literature review aims to provide a comprehensive and updated overview of the state-of-the-art regarding the use of biochar as an adsorbent in effluent treatment, contributing to the understanding and advancement of this research field.

Development

Biochar synthesis

Praveen et al. (2022) and Murtaza et al. (2022) state that commonly, biomass is converted into biochar through thermochemical conversion methods, which can be synthesized through hydrothermal carbonization, gasification, torrefaction, and pyrolysis.

Hydrothermal conversion involves the conjunction of raw materials and water in a closed reactor subjected to typically controlled temperatures around 180 to 250 °C. The byproduct of the process is called hydrochar, which can be classified into three categories based on temperature: gasification (above 400 °C), liquefaction (between 250 and 400 °C), and carbonization (below 250 °C). This method is commonly used for biomasses with varying moisture content. The characteristics of this biochar can be adjusted by controlling reactive temperature, heating rate, pressure, etc. (Saravanan & Kumar, 2022).

The process of converting carbon-rich materials into byproducts such as methane, hydrogen, carbon monoxide, etc., is referred to as gasification. This process is carried out at a constant temperature and involves the supply of oxidizing compounds formed by gaseous mixtures. Some fuel agents like carbon monoxide, carbon dioxide, and water are employed in the gasifier during this process. The composition of biochar can be affected by certain characteristics such as the type of oxidant used, residence time and temperature, particle size, and applied pressure. This process is recommended for samples with high moisture content and is commonly used due to the formation of synthesis gas and coal, albeit with a relatively lower yield (Ottani et al., 2022; Saravanan & Kumar, 2022).

Roasting constitutes a process of biological waste degradation under the effect of temperature, therefore emerging as an approach considering the minimal heating rate (mild pyrolysis). In this treatment, biomass undergoes a moderate decay process, generating condensable and non-condensable gases until reaching the biochar stage, also referred to as torrefied biomass. It may involve methods such as steam, moisture, and oxidation. The conventional temperature used for the process is 300°C, with a residence time below 1 hour and a heating rate of 50°C/min (Kwoczynski & Cmelik, 2021; Hu et al., 2022). According to Costa et al. (2023), it is common for the production yield of biochar to decrease with the increase in roasting temperature and increase as the residence time and burning temperature decrease.

The wet torrefaction process, in turn, is used in converting high-moisture biomass, considered advantageous compared to other methods due to its ability to alter certain chemical and physical properties of the torrefied wet biomass. This method can be regarded as a pre-treatment process for biomass in a hydrothermal medium or compressed hot water, where the pressure is slightly higher than saturated vapor pressure, which can reduce or avoid latent heat when the water remains in the liquid phase. Generally, this treatment is carried out under temperature conditions ranging between 180 to 260 °C, with a residence time of about 5 minutes (Costa et al., 2023).

While the production of biochar using pyrolysis, the most recurrent and popular process for its obtaining, requires the control of oxygen and a high temperature, surpassing 350°C, reaching temperatures close to 900°C under certain circumstances (Costa et al., 2023). The minerals present in the raw material play an important role in catalyzing biomass conversion, aiding in carbon stabilization (Islam et al., 2021; Buss et al., 2022). This is an excellent conversion method for generating biochar, synthesis gas, or bio-oil. According to Saravanan & Kumar (2022), in this type of treatment, cross-linking, depolymerization, condensation, and fragmentation of cellulose, lignin, and hemicellulose occur, resulting in gases, liquid residues, and the maximization of solid particles (Costa et al., 2023).

Table 1 gathers the different mechanisms of pyrolysis and the productive yield of biochars.

Table 1: Details of pyrolysis mechanisms and product yield.

Type of process	Pyrolysis temperature (°C)	Residence time	Heating (°C/s)	Performance
Slow pyrolysis	300 – 500	Hours/days 5 - 30	0,1 – 0,8	10% - 35%
Intermediate	300 – 450	Seconds to minutes	3 – 500	25% - 40%
Fast pyrolysis	300 – 1000	Hours	<10	30% - 60%
Hydrothermal carbonization	180 - 250	Hours	< 10	Cerca de 60%

Source: Adapted from Murtaza et al. (2022).

Characteristics of biochar

Various factors influence the efficiency of biochar. The chemical characteristics of the original biomass used as raw material subjected to pyrolysis, for example, are factors that directly relate to the adsorption capacity of the biochar. This could result in completely different properties for each material or even for a single material subjected to different types of processes or production conditions, depending on the characteristics of the biomass and the intended application (Nguyen et al., 2021).

The temperature plays a significant role in determining the characteristics of biochar due to the potential degradation and/or decomposition of organic materials such as cellulose, hemicellulose, lignin, etc. In this sense, the physical modification of biochar depends on the degree of decomposition of these constituents and also affects the ash content generated at the end of the process (Saravanan & Kumar, 2022).

In the case of productions through pyrolysis, the use of an optimal temperature, evaluated at 450°C, combined with a low supply of oxygen during the pyrolytic process, contributes to the enlargement of pores and the increase in functional groups. These factors can facilitate the interaction between solute and contaminant (Isaac & Siddiqui, 2022).

The structure and size of pores contribute to the increase in specific surface area. The formation of micropores contributes to the adsorption of contaminants on the biochar surface. Macropores, in turn, contribute to the adsorptive process of soil-liquid components (Saravanan, & Kumar, 2022).

The residence time of biochar during the production process also influences behavioral trends by altering properties. Murtaza et al. (2022) emphasizes that increasing this time at low temperatures (300°C) may result in decreased yield and an increase in pH. Conversely, increasing the residence time at high temperatures (600°C) slightly affects pH, yield, and the formation of functional groups. Another characteristic strongly affected by residence time is the specific surface area. In both cases, there's a need for in-depth analysis of the raw material and investigation into the adaptability of each process to the response of each material.

According to Pudelko et al. (2021) and Leng et al. (2022), the particle size of biochar is defined by the material's rigidity, having dimensions smaller than the raw material. Other factors such as density and pressure also contribute to the granulometric variability of the material. The mechanical stability of the material, in turn, contributes to maintaining its structure during ecological applications that involve flow and stress on the material.

Chemical characterization of biochar

Although biochar presents variations in its properties, even when applying a standard procedure in its production, there are several peculiarities that contribute to its utilization, whether in the field of pollutant bioremediation or in the mitigation of environmental impacts caused by the spillage of contaminating substances in soils. In this sense, it is essential that we recognize the main characteristics of each type of biochar to employ it in the most suitable way possible.

One of the main indicators of biochar quality is the specific surface area of the particles from the pyrolyzed biomass product. Additionally, its high fines content alters soil porosity and enhances productivity while maintaining water and nutrient retention.

The surface charge of biochars is strongly influenced by the pH of the solution in contact with them, which can become positively or negatively charged depending on the zero point of charge exhibited by the biochar. During the pyrolytic process, the thermal breakdown of cellulose, hemicellulose, lignin, starch, etc., coupled with the loss of water through material dehydration, leads to the formation of micropores with a high variability in size.

Most biochars have an alkaline pH, with few exceptions, and this characteristic is a consequence of the type of raw material used. This occurs due to the degradation resulting from the high pyrolysis temperatures, which tends to break down acidic functional groups.

Biochars are materials rich in functional groups OH, COOH, C=O, and NH2, enabling a higher adsorption capacity for various types of pollutants, and they can be easily synthesized with other functional materials (Pang et al., 2021). However, the formation of these groups essentially depends on the pyrolysis temperature used in the production process.

The Cation Exchange Capacity refers to the potential for retaining exchangeable cations, such as Ca2+, Mg2+, K+, Na+, and NH4+. It's a property involving functional groups and surface area, identified in biochars produced at relatively low temperatures.

The application of biochar in soil has a significant impact on the biodegradation, leaching, and sorption/desorption of organic contaminants. This process is influenced by the chemical composition and structure, porosity, surface area, pH, elemental proportions, and surface functional groups of biochar. These characteristics depend on the type of feedstock used, pyrolysis conditions, concentration, and nature of the organic pollutants it will interact with (Haider et al., 2022).

Biochar regeneration

The effectiveness of regeneration can vary among different adsorbents, depending on the specific characteristics of the biomass, biochar production conditions, and the types of pollutants available for remediation. There are several technologies available to treat various types of biochar, aiming for its regeneration and the reduction of associated costs.

Thermal regeneration is a low-cost option with considerable economic applicability. However, it tends to result in a higher carbon loss throughout the process. Regeneration using solvents also has low operational costs and involves relatively simple equipment and operations. Nevertheless, it's important to note the disadvantage related to equipment corrosion and the potential generation of secondary pollution (Khan et al., 2022; Costa et al., 2023).

On the other hand, microwave-assisted regeneration is characterized by precise temperature control and shorter process times. However, this technique requires more complex equipment and is associated with higher costs. Meanwhile, the regeneration approach using supercritical fluids presents complexities during the process, demanding greater attention in execution (Khan et al., 2022; Costa et al., 2023).

Use of biochar in soil improvement

Biochar is recognized for its high potential in improving soil conditions, owing to the high levels of inorganic elements present in its composition. These elements act as nutrients in the soil for plant growth, reducing the need for fertilizers and enhancing crop yields. Its water retention capacity also influences the required irrigation volumes, thereby reducing the need for irrigation (Haider et al., 2022).

The adsorption of cations and the increase in pH, especially in acidic soils, are the main factors responsible for the high nutrient retention capacity in soils amended with biochar. The increase in soil porosity and aeration, along with the rise in charge density and the enhancement of polar and non-polar sites through biochar addition, contribute to its use in soil improvement and nutrient availability (Haider et al., 2022; Murtaza et al., 2022).

The use of biochar as a means of soil operational correction in agricultural applications is feasible due to economic, sustainability, and environmental considerations. Additionally, utilizing residual materials such as food, agricultural, or municipal waste represents an economically beneficial endeavor.

In general, the life cycle costs of biochar, as well as its environmental effects, determine its economic viability in agricultural and environmental applications. Waste collection, raw material processing, pyrolysis operations, and the costs of handling and applying biochar must be continually weighed against the environmental benefits and improvements in agricultural production. The studies described below gather applications of different types of biochar for soil enrichment, correction, and enhancement in cultivation.

Virk et al. (2021) investigated the use of biochar water extract on the organic carbon mineralization in the soil. They examined two different cultivation methods at varying depths (0–10, 10–20, 20–30, 30–50 cm): rotational planting and no-till planting, subjected to hydration treatment using biochar extract and distilled water, respectively. The results indicated an increase in cumulative CO2-C emissions in the surface layer, which decreased with soil depth. Additionally, through no-till planting, a 13% increase in cumulative CO2-C emissions was observed. The stratified water increased microbial activity by 167% in the deeper layer. Furthermore, the increased microbial coefficient significantly reduced the values of organic carbon and pure carbon fractions in the soil. Overall, the addition of organic carbon through biochar to the soil enhances its mineralization by altering microbial activity.

Wijitkosum and Sriburi (2021) applied biochar produced from cassava stem pyrolysis to enhance low-fertility soil for maize cultivation. Eight experimental plots, replicated four times, were analyzed with varying doses of biochar applied. Cassava stem pyrolysis at temperatures between 450–500°C yielded highly alkaline biochar with a pH value approaching 9.6 and a high nutrient content. Specific surface area and total pore volume increased, falling into the mesoporous classification, while the average pore diameter decreased. The biochar's carbon content was highly stable, around 58.46%, displaying high aromaticity and polarity derived from the O/C and H/C ratios. Results indicated that the cassava stem biochar improved and supported maize growth, enhancing the soil's physicochemical properties for cultivation. Overall, biochar application led to higher maize yield and productivity compared to industrial fertilizers, offering a beneficial use for waste residues and generating a commodity with economic potential.

Abbas et al. (2022) assessed the impact of biochar application in irrigation and as a natural fertilizer for peanut production using a biochar whose raw material was not discussed. The results of the analysis of variance pointed to the efficiency in water use in irrigation management, different levels of biochar-based fertilizer, and their combined effects on total biomass, seeds, and pods, which were significant. The effect of irrigation management on the relative leaf water content was significant at a 5% probability level. Furthermore, the application of biochar-based fertilizer at a rate of 100 kg/ha yielded the highest peanut seed and pod yields.

Wang et al. (2022) investigated the long-term effects, approximately over four years, of two fertilizer management strategies (poultry manure compost versus mineral fertilizer) and soil amendment through biochar (0 versus 10 t/ha, using walnut shell biomass and a temperature of 900◦C for pyrolysis) on soil aggregation, soil organic carbon, and microbial dynamics in water-stable aggregate fractions for maize-tomato crop rotations. The application of walnut shell biochar, possessing highly recalcitrant properties, had limited long-term impacts on soil aggregation and carbon dynamics, likely due to the lack of available microbial carbon and limited interaction within the soil environment. Conversely, composting favored the proliferation of bacteria and fungi, contributing to the formation of macroaggregates.

Yuan et al. (2023) analyzed the application of biochar produced from corn straw at 400°C, combined with nitrogen fertilizers. It was observed that the use of the fertilizer alone and with the addition of biochar led to an increase in total soil nitrogen, as well as available nitrogen, and the presence of organic matter in the topsoil (0-20 cm) and subsoil (20-40 cm). Fertilizers, when used alone, resulted in the emergence of bacterial and fungal diversity, which did not occur with the application of biochar, a situation also observed by Wang et al. (2022). Biochar also contributed to weakening the competition and cooperation among microorganisms in the studied soil and subsoil, as well as alterations in key species of the networks due to the addition of biochar. In this sense, the presented data indicated that the addition of nitrogen fertilizers and biochar can contribute to improving soil fertility and the stability of structures in microbial communities present in the soil.

Li et al. (2023) investigated the applicability of biochar generated from cellulose factory plant residues in improving agricultural soils. They observed that the use of this material directly contributed to enhancing certain soil properties, benefiting the cultivation and production of specific crops. Overall, it was noted that applying Mg ha−1 year−1 on the planting surface over a 10-year period increased the physical and hydraulic indices of the soil up to a depth of 10 cm. The application of biochar to the cultivation soil reduced density and compaction levels, even without direct incorporation of the material due to the practice of no-till farming. There was also a substantial increase in soil aggregation, pore volume, and consequently, total porosity. Another significantly relevant characteristic related to crop growth is the soil's water retention capacity, which also increased with the addition of biochar. Furthermore, increased biochar usage in cultivated soils contributes to water availability for plants, reducing the need for irrigation and consequently, the production cost, especially during dry periods. Other characteristics such as increased field capacity and decreased permanent wilting point were also observed.

Based on the analysis from Table 2, we can observe that among the main applications of biochar is its use for improving soil properties, whether for increasing the productivity of a specific crop or for mitigating anthropogenic degradation. In all the studies, the application of biochar achieved its intended purpose and yielded positive results, demonstrating the environmental efficiency of applying biochar derived from different types of biomasses.

Table 2: Effects of biochar with different purposes.

Authors	Application of biochar	Resulting effect
Soares et al. (2021)	Added to the substrate of *Sapindus saponaria L.* seedlings, with and without the presence of biostimulants.	As the biochar content added to the substrate increased or decreased, there were changes in the total height of the seedling, stem diameter, root volume, and root length. The aboveground-to-root mass ratio showed better results, in the absence of the biostimulant, with a 21.7% proportion of biochar added to the substrate. Moreover, concerning the total height to stem diameter ratio, the influence of adding both the biostimulant and biochar maintained a balanced biomass distribution in *Sapindus saponária* seedlings.
Tavares et al. (2021)	Improvement of carrot cultivation productivity.	Biochar has proven to be an excellent conditioner in improving the properties required for cultivation. Additionally, it increased the diameter of carrots and the length of the roots. It was also observed that smaller additions of biochar resulted in better cultivation outcomes.
Bal et al. (2021)	Removal of Methylene Blue dye using pumpkin peel biochar.	Biochar has shown higher adsorptive potential within a preferred pH range, varying between 6.0 and 9.0. The maximum adsorptive capacity exhibited by biochar was 208.3 mg/g, indicating the material's effectiveness in treating wastewater containing Methylene Blue.

Ramesh et al. (2022)	Remediation of Turquoise Blue Dye using Prosopis Juliflora Biochar.	The highest pollutant adsorption capacity was observed for the adsorbate at a concentration of 200 mg/L with a contact time of 6 minutes and pH 6. The maximum adsorption capacity was noted in Langmuir isotherms at 0.005173 mg/g, indicating a good retention capacity.
Carvalho et al. (2022)	The effect of application on the chemical properties of two types of soil: Eutrophic Red-Yellow Latosol (LVA) and Dystrophic Red-Yellow Argisol (PVAd).	In both soils, the addition of biochar increased the organic matter content. Additionally, the phosphorus content showed a significant increase only in the eutrophic Red-Yellow Latosol.
Qin et al. (2023)	Remediation of the antibiotics tetracycline and ciprofloxacin using poplar biochar.	The poplar residues were converted into biofuel and biochar through pyrolysis. The resulting biochar exhibited high rates of ZnO and Fe3O4, along with a high specific surface area, demonstrating efficiency as an adsorbent and photocatalyst for eliminating tetracycline and ciprofloxacin, achieving adsorption of up to 316.41 and 255.23 mg/g, respectively. Additionally, it reached nearly 100% photocatalytic degradation.
Williams et al. (2023)	Use of rice husk biochar for increased soil productivity.	Biochar has shown the ability to improve average productivity by 230% across three types of crops. Additionally, the material was responsible for increasing substances such as phosphorus and zinc in the soil, enhancing yields in acidic, neutral, and alkaline soils..

Use of biochar in the sorption of contaminants

The treatment of various types of industrial and agricultural pollutants, characterized by high toxicity and contaminant content, has driven the study and implementation of low-cost techniques and materials for alternative treatment. Biochar stands out as one of the most relevant methods (Ravindiran, Sugumar, & G, 2021; Ambaye et al., 2020; Haider et al., 2022; Rubangakene et al., 2022; Sawalha et al., 2022).

The breakdown of organic contaminants and their conversion into environmentally suitable and stable products is termed degradation. This process can be achieved through various biotic or abiotic methods, utilizing processes such as biodegradation, photolysis, hydrolysis, oxidation, film diffusion, pore dispersion, and particle transport (Haider et al., 2022).

In this aspect, the physicochemical characteristics of biochar influence the sorption/desorption of contaminants. Properties such as biochar structure, chemical composition, porosity, surface area, electrostatic interaction, pH, and functional groups are the main factors responsible for the occurrence of adsorptive phenomena towards these compounds (Haider et al., 2022; Rubangakene et al., 2022).

Two other characteristics of fundamental relevance to the adsorptive process of biochar are the surface charge, typically negative, which enhances the interaction between biochar and cationic compounds, and porosity, which, when associated with the presence of functional groups, contributes to the increased adsorption capacity of contaminants, essentially heavy metals (Sackey et al., 2021; Chen et al., 2022; Krishnasamy et al., 2022).

The following analyses gather demonstrations of applications of a wide range of biochars in remediating pollutants such as dyes, heavy metals, antibiotics, and pesticides. These pollutants constitute the vast majority of effluents originating from industrial and agricultural activities, which end up being released into the environment, compromising the quality of natural resources and threatening people's quality of life (Krishnasamy et al., 2022; Pipeuška et al., 2022).

Adamu et al. (2022) investigated the potential for removing the dye Vivizole Red 3BS using biochar derived from coffee grounds. The biomass was carbonized with an iron (III) salt catalyst, which contributed to the formation of a greater number of functional groups. Employing a predictive model based on response surface methodology and batch adsorption studies using kinetics and isotherms, they achieved an efficiency of 60% for the pure biochar. This was assessed by fitting the Langmuir isotherm model, which exhibited an average adsorptive capacity of 2.07 mg/g. Kinetic equilibrium data, described through the pseudo-second-order model, indicated a spontaneous and favorable adsorption process involving both physical and chemical adsorption mechanisms.

Han et al. (2021) used biochars from corn straw, rice straw, and bean stalks to analyze their capacity for reducing the azo dye Methyl Orange through the action of sulfides. The rice straw biochar, produced at 800°C, exhibited the most effective degradation among the materials, with a degradation rate of 96.6% in 40 minutes and 100% in 50 minutes. The degradation mechanism was based on redox reactions, and the data fitted the Gompertz model. The authors also highlighted the materials' adaptability to variations in temperature and pH, which could result in the increase or decrease of sulfides. Additionally, compared to commercially available materials with the same purpose, the biochar showed a higher number of pores and greater cost-effectiveness. According to Sackey et al. (2021), azo dyes are considered one of the most toxic pigmenting materials to the environment and humans.

He et al. (2022) assessed the application of biochar produced from sewage sludge synthesis obtained from a water treatment plant for Congo Red dye removal. The optimal production condition observed for the biochar was pyrolysis at 400°C for 4 hours, resulting in a substantial increase in specific surface area and a porous structure. The best adsorptive condition was observed at a pH value of 7. The best fit was observed through the pseudo-second-order model, indicating that the main controlling step was the chemical adsorption process. Using the isotherm model, an adsorption of 116.4 mg/g was observed, with the fit achieved through Langmuir.

Kapoor et al. (2022) assessed the use of biochar produced from banana peels for Reactive Black 5 dye removal at a concentration of 75 mg/L. The results were fitted using the Langmuir isotherm, exhibiting a 97% removal of the dye and a maximum adsorption of approximately 7.58 mg/g at a pH range of 3. Kinetic parameters indicated an adsorptive process governed by physisorption of the compounds. Furthermore, the trials demonstrated that the biochar showcased excellent regeneration capacity after five successive cycles of adsorption-desorption, enabling its reuse in similar processes, reducing the need for replacement and discarding of this material post-contamination.

Castro et al. (2022) used biochars produced from coffee husks at temperatures of 400, 500, 750, and 900 °C for removing the dyes Trifenylmethane, Pararosaniline, and Methyl Violet 10B. FTIR and Raman analyses indicated that an increase in the pyrolysis temperature contributed to the aromaticity of the biochar's surface structure while reducing the number of oxygenated functional groups. The most favorable adsorption data were observed at a pH range around 7.5, with an approximate adsorptive trend for the biochars produced at 900 and 750°C, increasing as the temperature decreased for both dyes. The adsorption value for the most satisfactory result biochar, produced at 400°C, was 1.3 times higher for the Pararosaniline dye, at about 92.22 mmol/kg, and 1.9 times higher for Methyl Violet 10B, at 5.49 mmol/kg. The Langmuir model provided the best fit for the adsorption isotherms of the biochars at 400 and 900 °C, while the others were fitted by the Dubinin–Radushkevich model. This study revealed that the increase in pyrolysis temperature reduced the number of adsorption sites where the dyes interacted favorably through hydrogen bonding.

Bazan-Wozniak et al. (2022) analyzed the potential for removing the dye Methylene Blue and the inorganic gas (NO_2) using biochar produced from nettle seeds at temperatures of 600 and 700 °C. Through kinetic and isotherm tests, the authors identified an adsorption capacity of 150-239 mg/kg of dye for each respective biochar. Kinetic data fitting was best described by the Langmuir model, while the kinetic data was fitted using the pseudo-second-order model, indicating the occurrence of a spontaneous endothermic reaction. Sorption analysis for the gas showed lower results, with an average sorption of 59.1 mg/g of NO_2 for both biochars. The sorption data obtained for the dye indicates that the increase in pyrolysis temperature favored the adsorptive process.

The removal of the Methylene Blue dye was also analyzed by Diaz-Uribe et al. (2023), who used biochars produced at different temperatures (300, 500, and 700°C) from Prosopis juliflora residues, a plant species identified in tropical forests. The adsorptive analysis was conducted using the biochar produced at 500°C due to its significant specific surface area (1.28 m²/g) compared to the others. The isotherm results were fitted using the Freundlich model, while the kinetics employed the pseudo-second-order model. The highest removal value observed was 2.94 mg/g, while the cycling test indicated a high saturation capacity of the biochar, suggesting its potential for continuous use until its efficiency decreases.

Efficient results in Methylene Blue adsorption were also observed by Eldeeb et al. (2022) using kinetic and isotherm assays involving the application of purified sawdust biochar, obtaining adsorption data at approximately 769 mg/g sorption rate, fitted to the Langmuir isotherm model. Kvorkova, Sirotiak, & Hajzler (2022) also employed sawdust-derived biochar using a slow pyrolysis process for Methylene Blue sorption. Sorption rate was determined through absorbance readings at a wavelength of 665 nm. The results demonstrated a satisfactory adsorption rate equivalent to 95%.

The application of biochar-based nanobiosorbents has also been discussed as an alternative for dye treatment. Rubangakene et al. (2022) utilized the biochar/zeolite nanocomposite produced through thermocatalytic degradation at 450°C. In this study, they applied the cationic dye Methylene Blue and the anionic dye Congo Red. The maximum observed efficiencies for the dyes were 87.5% (pH 12) and 84.1% (pH 2), respectively. For both cases, an equilibrium time of 60 minutes was observed, with an optimal dosage of 5 g/L. The best data fittings were observed using the Langmuir isotherm model and pseudo-second-order kinetics for the reactions.

The application of biochars associated with zero-valent iron nanocomposites has been an alternative assessed to improve the reactive process. Imran et al. (2022) employed a biochar obtained through pyrolysis at 450 °C of Eleocharis dulcis, a grass species, associated with zero-valent copper and magnetite nanocomposites for Congo Red dye removal. The data indicated an adsorptive advantage resulting from the application of nanocopper, approximately 212 mg/g. When applied alone, the biochar retained around 174 mg/g of the material. Isotherm adjustments were conducted using the Freundlich model, while kinetics employed the pseudo-second-order model. Through fixed-bed columns containing 3 g of each material, the authors observed a 99% removal of the dye, even at a high concentration of 500 mg/L.

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It is known that different types of industrial effluents carry in their composition a wide range of heavy metals that, for the most part, cannot be fully degraded through biological processes in nature. Furthermore, the bioaccumulation capacity of these materials contributes to their persistence in the environment, negatively impacting the productivity of certain crops and posing a potential risk to human and animal health (Burachevskaya et al., 2023).

In this regard, aiming to reuse sludge from residual treatment plants, Khan et al. (2022) assessed the use of this material in biochar production and its application in remediating dyes and heavy metals in textile effluents. The study concluded that the presence of functional groups on the algae-derived biochar surface holds significant importance in removing these contaminants and that these groups are strongly influenced by the temperature of the thermochemical processes involved in biochar production. Furthermore, modifying the biochar can enhance its decontamination potential.

Gu et al. (2023) used two types of biochars, one derived from crayfish shells (Procambarus clarkia) and Chinese banyan branches (Ficus microcarpa). The application of both biochars resulted in a decrease in lead concentrations by 26.8% and 28.8%, respectively. They concluded that the biochar obtained from a plant-based matrix has a greater capacity for heavy metal removal.

Yang et al. (2022) investigated the kinetic stabilization of heavy metals zinc and cadmium using biochar derived from the co-pyrolysis of coconut fiber and sewage sludge. Their data revealed a significant reduction in zinc and cadmium levels in the acid-soluble and reducible fractions within the sludge after co-pyrolysis with coconut fiber. However, there was a notable increase in their levels within the residual fraction, thereby decreasing the ecological risk associated with the biochar. Through adjustments using kinetic models and Freundlich adsorption of ciprofloxacin onto the biochar, a multi-layer chemisorption process was observed. Consequently, sewage sludge biochar with coconut fiber diminishes the risk posed by heavy metals by exhibiting enhanced capacity for adsorbing ciprofloxacin from water.

Li et al. (2022) evaluated the application of biochar, focused on utilizing cotton waste, for the removal of the heavy metals lead and cadmium. It was produced through a hydrothermal carbonization process. Through Fourier Transform Infrared Spectroscopy analysis, it was possible to identify that the material contained a large number of surface functional groups. The biochar adsorption for lead and cadmium was 50.44 mg/g and 33.77 mg/g, respectively.

Assirey and Altamini (2023), considering the wide range of cultures that use corn as their main food base, investigated the conversion of corn cobs into biochar for removing contaminants in wastewater. The research identified that biochar subjected to higher pyrolysis temperatures (450 °C) possessed a larger specific surface area, about 80 times the surface area of biochar subjected to 350 °C. Additionally, the total pore volume was 77.5 times greater in the biochar produced at the higher temperature. The authors noted that the adsorption of lead increased with the rise in pH, and similarly, the increase in pyrolysis temperature had a significant impact on the material's performance in metal adsorption. For both biochars, the adsorption equilibrium followed the Langmuir equation, displaying a high correlation coefficient. Considering that the sorption energy was very close for the two available temperature settings, the positive value indicates the occurrence of an endothermic adsorption reaction, suggesting the presence of physical or chemical sorption, thereby making it useful for decontaminating waters containing heavy metals.

Focusing on the issue of surplus agricultural waste from rice and sunflower husks, Burachevskaya et al. (2023) analyzed the potential for heavy metal removal by biochars produced from both biomasses, comparing them to wood-based biochar, for remediating heavy metals such as copper, zinc, and lead. The researchers identified that the increased soil adsorptive capacity in the presence of biochar is justified due to its chemical and physical properties, including functional groups, mineral content, zeta potential, specific surface area, and pore volume. The highest adsorptive capacity was observed for lead, with a removal rate of about 95%. Furthermore, adsorption tests demonstrated that wood-based biochar yielded better results due to its larger specific surface area and a higher number of aromatic functional groups. Although crop residue biochars had lower performance compared to wood-based biochar, their results were still satisfactory when compared to the pure soil's metal retention capacity. However, considering the economic factors involved in material production, the use of rice and sunflower husk-based biochars outweighs wood-based biochar.

Similarly, Pinnamaneni et al. (2023) observed improved cotton productivity in infertile soils with elevated acidity levels through the combined application of sugarcane-based biochar and plant residues over a three-year period. In the first year, mixed results were obtained across the planting area, with a trend of productivity enhancement following successive biochar applications. It was evident that this increase stemmed primarily from nitrate leaching and the augmentation of nitrogen and organic carbon in the soil. Moreover, owing to the pelletized nature of the biochar, which demands time for physical and microbial breakdown, the peak of its effect is experienced after a certain period, gradually aging as it becomes slowly incorporated into the soil.

Different research studies aimed at remediating heavy metals have been working with the hypothesis of improving biochar through its enrichment, modification, and chemical addition, also known as activation. The primary goal is to enhance biochars so that specific properties are strengthened, thereby expanding their potential for removal through the predominant adsorptive mechanism identified in each type of material.

Song et al. (2021) analyzed the passivation and remediation of soil contaminated by cadmium using a calcium-modified biochar. They also assessed changes in the physicochemical characteristics of the soil and the accumulation of cadmium in plants. It was observed that the effective cadmium content in the soil decreased by 12–30.2%, and the morphology of cadmium in the soil shifted from more active exchangeable and reducible states to the residual state, which appears to be more stable.

Gondek et al. (2023) investigated the effectiveness of using biochar and zeolite in the remediation of soils contaminated with heavy metals such as Cd, Pb, and Zn. Both biochar and zeolites have the ability to adsorb, exchange ions, and complex heavy metals, reducing their mobility and bioavailability in the soil. The experiment utilized different types of grasses and varied soil treatments, finding that supplementing the soil with these functionalized materials reduced the mobile and carbonatic forms of the metals. Although biochar and zeolite showed moderate effectiveness when applied separately, more promising results were observed when used together. The two-year study emphasized the importance of time in observing significant changes in bioavailable metal concentrations. Additionally, promoting soil enzymatic activity through the application of these materials was associated with changes in soil chemical properties, such as pH and electrical conductivity.

Herath et al. (2021) proposed the application of a modified biochar derived from Douglas fir for the removal of lead, chromium, and cadmium from aqueous solutions. The biochar was obtained through rapid carbonization using high temperatures and was modified by the addition of KOH. Experimental results showed that the surface area of the material increased from 535 m2/g without modification to 1049 m2/g post-process, and the adsorption capacities for the heavy metals lead, chromium, and cadmium were up to 140.0, 127.2, and 29.0 mg/g, respectively, under optimal pH conditions for each heavy metal.

Based on the adsorption mechanisms of biochars, Wang, Li, & Lin (2022) evaluated the efficiency of modified species to identify an effective material for heavy metal treatment. Through the results, it was identified that different types of biochars have a high adsorptive effect in removing heavy metals; however, their saturation contributes to limitations that affect the adsorption capacity. To improve biochar efficiency, it is essential to modify it. There are different methods for biochar modification, among which the authors highlight physical, redox, acid-base, composite modification, and activation. These alterations contribute not only to the fixation of heavy metals in contaminated substrates and soils but also reduce the content of these compounds to break the cycle of bioaccumulation.

Another compound that has shown high contaminating potential and requires significant attention in attempting to establish low-cost treatment methods, or even for the recovery of affected soils, is pesticides and herbicides. These substances are responsible for increasing agricultural yield and productivity; however, their use can negatively impact human health and ecosystem balance, as certain pesticides can be inherently recalcitrant. Among the techniques being used for sustainable remediation, adsorption is considered highly efficient and can also be implemented on a large scale (Ogura et al., 2021; Bose et al., 2023; Costa et al., 2023).

Batool et al. (2022) used zerovalent iron supported on a biochar nanocomposite synthesized from Nephelium lappaceum (Rambutan) peel waste as an adsorptive medium, applied for the simultaneous removal of 6 selected organochlorine pesticides (OCPs) from an aqueous medium. In this context, Rambutan was used as a green reducing mediator to reduce zerovalent iron. The characterization study confirmed both the synthesis and dispersion of iron nanoparticles on the biochar surface. Batch experiments indicated an efficiency potential of 96-99% and 83-91% removal within 120 and 150 minutes, respectively, at an initial pH of 4. The OCP adsorption isotherm fitted well with the Langmuir isotherm followed by the Freundlich isotherm. The experimental kinetic data were fitted to the pseudo-second-order and then the pseudo-first-order reduction kinetic model. It was found that the main adsorption mechanism involves x-x electron donor-acceptor interaction, facilitated by hydrophobic sorption and pore filling.

The contamination by pharmaceuticals has also raised significant concern, especially due to their characteristics of bioaccumulation and ecotoxicity. Overall, antibiotics are among the widest spectrum of pharmaceutical components used in various areas of human and veterinary medicine (Yang et al., 2021; Ji et al., 2022; Li et al., 2023). For this reason, different researchers have been dedicated to addressing this issue, aiming to reduce the impacts resulting from the release of these contaminants into the environment.

Velusamy et al. (2021) applied walnut seed-derived biochar in the retention process of ciprofloxacin. The biochar exhibited excellent contaminant adsorption at pH 6 and a temperature of 29.85°C. The removal capacity through the Langmuir isotherm model was 33.44 mg/g, while the Freundlich model provided the best fit when the dosage was 0.07 g. It was also observed that the ciprofloxacin adsorption process showed good fitting through the pseudo-second-order kinetic equation, with the intraparticle diffusion mechanism primarily controlling the process. Walnut seed biochar proved to be an excellent low-cost adsorbent for removing ciprofloxacin from wastewater.

Zheng et al. (2022) applied a sludge-derived biochar, modified by dual hydroxides, as an adsorbent and oxidant for ciprofloxacin removal. Under ideal conditions, the ciprofloxacin removal rate is elevated by 24% compared to pure biochar. Meanwhile, the removal rates of total organic carbon and total nitrogen in the modified form are increased by 24% and 27%, respectively. Investigation into the mechanism suggested that the specific surface area and adsorption sites of the modified biochar experienced a significant increase, leading to more ciprofloxacin being adsorbed onto the composite surface and subsequently oxidized by additional persistent free radicals.

Ji et al. (2022) used a self-modified biochar catalyst synthesized from chicken manure to degrade levofloxacin hydrochloride. The degradation rate of levofloxacin hydrochloride reached 89% within 40 minutes after using three cycles of the catalyst, with the compound maintaining degradation at 52% thereafter. It was also observed that at low concentrations, levofloxacin hydrochloride could achieve an even more satisfactory removal potential, as the degradation rate could reach 99% within 40 minutes.

Li et al. (2023) used a biochar produced from doped nitrogen-enriched herb residue for the removal of tetracycline. The observation of radical elimination activities through Electron Paramagnetic Resonance Spectroscopy (EPR) revealed that singlet oxygen is the primary oxidative reactive species. Batch experiments showed satisfactory degradation results through excellent photocatalytic performance and degradation. The best condition for tetracycline degradation efficiency (>99%) was observed at 60 minutes when the biochar dosage was 1 g/L at a peroxymonosulfate concentration of 5 mM.

Hou et al. (2023) used wheat straw-derived biochar, employing different zinc chloride rates as opening regulators, followed by sulfamethoxazole adsorption. The results obtained from the adsorption isotherms indicated an adsorptive increase of the biochar from 29 to 54 times due to the treatment using ZnCl2, with the initial adsorption in the range of 11.04 mg/g for an initial concentration of 30 mg/L of the antibiotic. The kinetic curves indicated an increase in adsorptive capacity for the first 10 minutes due to the presence of new adsorbents, providing sufficient adsorption sites for sulfamethoxazole retention. As the adsorption process occurred, the increase in adsorption capacity was perceived by the flattening of the kinetic curve, indicating that the occupied adsorption sites tended towards saturation. It was also observed that the pH variation from 3 to 11 demonstrated two trends: the first showing an increase in adsorptive capacity in the 3-4 range and a decrease in this capacity for the 4-10 range, characteristics inherently linked to the chemical structure presented by sulfamethoxazole.

Qi et al. (2023) observed an increase in bacterial growth, responsible for the reduction of saturated fatty acids to total fatty acids, which contribute to the biodegradation of sulfamethoxazole and chloramphenicol due to the addition of dissolved organic matter derived from biochar. The results obtained for sorption kinetics demonstrated that the byproduct decreased the adsorption equilibrium time for both antibiotics, favored the adsorption of sulfamethoxazole, and inhibited the adsorption of chloramphenicol.

Results and discussion

In the realm of soil enhancement, applications involving various types of biochars have proven satisfactory, particularly in enriching the soil and correcting specific properties for agricultural purposes. Different authors have observed an increase in soil carbon content when utilizing biochar as a natural fertilizer alternative, although its function may not necessarily serve as a direct replacement for inorganic fertilizers, as emphasized by Pinnamaneni et al. (2023).

A wide range of positive effects of biochar on the soil have also been observed, such as a significant increase in water retention capacity upon biochar addition, which can be attributed to the material's unique porosity and its ability to enhance soil structure. Furthermore, biochar has proven to be effective in retaining nutrients such as nitrogen, phosphorus, and potassium, acting as a reservoir for slow-release nutrients. These findings support previous studies and underscore the role of biochar in improving soil fertility. It is worth noting that within the context of climate change projections over recent years, the enhancement of soil water retention capacity and the consequent reduction in the need for irrigation and cultivation further emphasize the necessity of adopting this material for water conservation.

Another crucial aspect elucidated in this study is the influence of biochar on soil biological activity. It was found that biochar promoted the growth and activity of beneficial microorganisms in the soil. This can be attributed to creating suitable habitats for these microorganisms, as well as biochar's ability to adsorb organic compounds that serve as a source of microbial food. Promoting biological activity is a determining factor for the overall health of the soil and its ability to sustain plant growth.

When it comes to treating contaminated effluents, the main interaction mechanisms for sorption of contaminants—be they dyes, heavy metals, pesticides, or pharmaceuticals—involve characteristics such as high cation exchange capacity, electrostatic interaction, porosity, and specific surface area, as highlighted by Assirey and Altamini (2023). A considerable portion of research works on the sorption capacity of biochars emphasize the potential of these materials in mitigating environmental pollution while also raising concerns about the saturation of sorption sites over time, indicating a concern regarding the efficiency limits of these materials and their regenerative capacity.

Considering the particularities arising from the variability of materials used in biochar production and their corresponding properties, it's possible to observe that the adsorptive behavior displayed by these materials, essentially linked to their capacity for chemical, physical, and/or electrostatic interaction with compounds of different natures, does not follow a continuous line of effectiveness and efficiency. It can abruptly vary depending on the type of contaminant it comes into contact with. Similarly, a biochar that didn't yield satisfactory results for a specific compound doesn't necessarily imply its inefficiency in other applications, as observed by Burachevskaya et al. (2023).

It's also possible to observe, through the analyzed studies, that the manufacturing temperature of biochar, as well as the pyrolysis process or other biomass syntheses, directly influence the pH and sorption capacity of these materials, both positively and negatively, depending on the pollutant with which it may interact (Assirey and Altamini, 2023).

In studies related to dye remediation, most of the adsorption results were fitted using the pseudo-second-order kinetic model and the Langmuir isotherm. In all cases, satisfactory adsorption rates and/or reactive processes were observed. In certain instances, the enhancement of biochar properties contributed to increasing its efficiency, demonstrating that such materials can acquire greater adsorptive capacity through the correction of their properties.

About heavy metals, the identified applications of biochar have also shown positive results, with high removal rates. However, the improvement of these materials' properties through physical and chemical means had an even more positive impact in various situations, contributing to the reflection on the limits of chemical and physical interaction of biochars in their natural form.

When it comes to pesticides and pharmaceuticals, a significant portion of natural biochars have shown satisfactory removal and degradation results, with high removal rates that significantly depended on temperature and pH of the environment. Most reactions were governed by the chemical interaction between the biochar and the contaminants.

Conclusion

This way, it's possible to conclude the remarkable bioremediation capacity of biochar in reducing concentrations of pollutants improperly discarded into the environment. Similarly, recognizing its positive influence when applied to restore degraded soils with low productivity, enhancing carbon levels, water retention, and nutrients. In addition to biochar being a material produced at relatively low costs, it offers a wide variety of potential biomass sources, which can be used for its production, making it feasible for its application as a less expensive sorbent compared to available market treatment techniques. Moreover, it often contributes to better disposal of waste materials, providing the opportunity to form cyclical chains through the reuse of discarded materials.

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