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Carbon-based catalyst for environmental bioremediation and sustainability: Updates and Perspectives on Techno-economics and life cycle assessment

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Abstract

Global rise in the generation of waste has caused an enormous environmental concern and waste management problem. The untreated carbon rich waste serves as a breeding ground for pathogens and thus strategies for production of carbon rich biochar from waste by employing different thermochemical routes namely hydrothermal carbonization, hydrothermal liquefaction and pyrolysis has been of interest by researchers globally. Biochar has been globally produced due to its diverse applications from environmental bioremediation to energy storage. Also, several factors affect the production of biochar including feedstock/biomass type, moisture content, heating rate, and temperature. Recently the application of biochar has increased tremendously owing to the cost effectiveness and eco-friendly nature. Thus this communication summarized and highlights the preferred feedstock for optimized biochar yield along with the factor influencing the production. This review provides a close view on biochar activation approaches and synthesis techniques. The application of biochar in environmental remediation, composting, as a catalyst, and in energy storage has been reviewed. These informative findings were supported with an overview of lifecycle and techno-economical assessments in the production of these carbon based catalysts. Integrated closed loop approaches towards biochar generation with lesser/zero landfill waste for safeguarding the environment has also been discussed. Lastly the research gaps were identified and the future perspectives have been elucidated.

Keywords: Biochar; Pollution control; Techno-economical assessment; Composting; Environmental remediation; Sustainability

1. Introduction

Rapidly expanding human population and industrialization have resulted in an increase in global energy demand and thereof the production has not been able to keep up with the rising need (Zhou et al., 2021; Ahuja et al., 2022). Lively urbanization and growth in population have also led to the increase in pressure on agriculture sector that extremely affected the soil productivity and to fulfill the growing food demands, the excessive usage of pesticides and chemical fertilizers resulted in emission of greenhouse gas (Gaur et al., 2021a; Gaur and Manickam, 2021; Vijay et al., 2021; Vyas et al., 2022a). However, these may also lead to the excessive generation of organic wastes such as agro-industrial wastes, municipal solid wastes, water wastes, food and animal manures and other wastes etc. (Gaur et al., 2021b; Pandey et al., 2021; Sharma et al., 2021, 2020; Vyas et al., 2022b). Therefore, utilization of organic wastes for biochar production is considered viable for addressing such issues and is being focused around the world for its possible benefits (Table 1) (Gabhane et al., 2020; Ghodake et al., 2021).

Biochar is a biologically derived carbonaceous solid product produced by processing biomass at 700 ºC in the presence or absence of very little oxygen (O_2) supply during the slow pyrolysis process. Carbon based biomass-derived solid, gas and liquid fuels as well as chemicals may be produced using various valorisation technologies such as hydrothermal carbonization, liquefaction, gasification, pyrolysis, and microbial engineering (Fig. 1) (Zhou et al., 2020). Amongst them pyrolysis, the thermochemical process for conversion of biomass is considered as one of the modern techniques for the synthesis or production of biochar. Biochar possesses unique physio-chemical properties such as high porosity, large surface area, functional groups, structural stability, high cation exchange capacity, electrical conductivity, water holding capacity, etc (Yaashikaa et al., 2020). Temperature, type of biomass, residence time, rate of heating, and pressure are some of the factors that affect the properties of biochar

(Yaashikaa et al., 2020). Biochar is widely used, particularly for environmental protection, because of its carbon-richness and minimal cost, eco-friendly nature and great level of adaptability (Zhou et al., 2021). Biochar has gained promising attention on climate change, agriculture, and soil health (Arif et al., 2020). Biochar has been thoroughly researched for enhancing soil fertility, seed germination, plant vegetative growth, increasing disease resistance, adsorbing hazardous pollutants, improving land water holding capacity, and carbon sequestration, and GHG emissions reduction, composting, wastewater treatment, soil remediation, energy production, and as catalyst (Gabhane et al., 2020). Several researchers investigated the biochar benefits to the composting process that reduces the rate of greenhouse gas emission, reduces ammonia loss, organic matter degradation and humification and also acts as bulking agent for compost (Camps and Tomlinson, 2015). Apart from all these there has been a scarcity in the literature for the life-cycle and techno-economic analysis on the application of biochar.

Furthermore, it is widely recognized as a suitable framework for the development of a wide range of different functionalized carbon materials for future catalytic, energy, and environmental applications (Kundariya et al., 2021; Zhou et al., 2021). Furthermore, due to the increasing application of biochar and its synthesis by using waste has we undertook this study to highlight the advances in the utilization of waste as feedstock for the production of biochar. The methods employed for the activation and synthesis of biochar has been discussed. Followed by the techno-economics and life cycle assessment of the product along with its application in environmental bioremediation to energy storing device. The research gaps and future research direction has been identified and discussed.

2. Biomass/Feedstock selection

Rapid human population growth and industrialization have resulted in an increase in energy supply, and source of energy production has not been able to keep up with the rising need (Gaur et al., 2022; Patel et al., 2021). Biomass is an organic substance derived from living organisms that stores energy (mostly carbon). As a result, biomass has been extensively researched and used as a raw materials for the generation of solid, gas and liquid fuels to replace fossil fuels (Leng et al., 2019, 2018; McKendry, 2002; Varjani et al., 2021; Uthirakrishnana et al., 2022). After conventional energy sources, biomass is the 4th biggest energy system, accounting for 14% of worldwide annual energy consumption (Xu et al., 2019). The abundance of feedstock, quick availability, and cheap cost are among the most significant characteristics for selecting sustainable biomass feedstock for biochar manufacturing (Jang and Kan, 2019). Biochar is a carbon-rich solid made from biomass feedstocks that have undergone reductive thermal processing and/or pyrolysis (Fakayode et al., 2020) and the quantity of carbohydrate in the feedstock determines how much biochar can be produced (Adesra et al., 2021). Biochar yields are greater in feedstocks with higher carbohydrate content (Ponnusamy et al., 2020). The biochar characteristics are largely influenced and regulated by the type of biomass feedstock used (Table 1). Various biomass wastes, such as animal and plant leftovers, and sewage sludge, can be used as alternative feedstock sources (Mohanty et al., 2021; Giri et al., 2021). However, unregulated use of some feedstock may contain toxicants (heavy metals) and biological (pathogens) hazards to human health and the environment (Usmani et al., 2020). By separating and banning contaminated feedstock/biomass at the start of the biochar manufacturing process, possible sources of risks may be identified and avoided. Cellulosic biomass and algal biomass were the two most prevalent feedstock(s) used to produce high-quality biochar (Ponnusamy et al., 2020; Varjani et al., 2020). However, feedstock selection is based on physio-chemical parameters and biomass characterisation (evaluation of the components present in the product, such as percentage of ash and moisture content, ratio of carbon, hydrogen, oxygen, nitrogen, sulphur, fixed carbon and volatiles and chlorine etc.) (Fakayode et al., 2020). Carbohydrates, lipids and proteins are the essential ingredients of macroalgae biomass, whereas lignin, cellulose, and hemicellulose are major lignocellulosic biomass components (Wang et al., 2018a). The differences in the chemical and structural properties of the feedstocks, which are connected with their certain ingredients and play a key role in biomass selection, produce the varied thermal degradation behaviour (Mishra er al., 2020). Degradation of lignocellulosic biomass occurs mostly at temperatures between 160-900 ºC (Yang et al., 2007), whereas dehydration happens at 200 ºC, followed by devolatilization (200-600 ºC), and decomposition (500 ºC) for macroalgae biomass (Uzoejinwa et al., 2018). Aside from that, a variety of factors impact biochar production, including the degree of pre-treatment of biomass feedstock, processing parameters (most notably the reaction temperature and duration), and pre- and post-processing needs including drying, chilling, size, shape, and condensation (Fakayode et al., 2020). The advantages and disadvantages of biochar have been discussed in Table 2. In summary, biochar has various qualities, including the ability to hold water, function as an adsorbent, contribute nutrients, sequester carbon, and sustain soil biodiversity.

3. Factors affecting biochar production

Biochar has a diverse origin depending on the feedstock and exhibits diverse properties (; Ahmad et al., 202). The characteristics and efficiency of biochar depend on various factors including types of feedstocks, moisture content, heating rate, and temperature (Table 3).

3.1. Feedstock / biomass type

The type of biomass employed is the most important factor that determines the property of biochar. The factors like nature and environmental conditions during crop cultivation play a critical role in defining the quality of feedstock (Xu et al., 2018; Yaashikaa et al., 2019a). This quality affects the carbon and ash content of biochar and its carbon sequestration capacity. The presence of lignin content in feedstocks enhances the carbon content of biochar (Pandey et al., 2020). The majority of feedstocks were obtained from wood, agricultural, industrial, and municipal wastes (Varjani et al., 2019; Xu et al., 2018).

Biochar derived from wood residues are microporous, have high surface area, low ash, low moisture, and high stability due to the presence of lignin content and aromatic carbons whereas biochar from agricultural feedstocks contains more functional groups like hydroxyl, carboxyl and had better yield but low lignin content and thus it results in low stability (Pandey et al., 2020; Tomczyk et al., 2020; Xu et al., 2018). In a recent study, the leaves of a famous biodiesel plant named *Jatropha curcas* yielded 53.3 ± 9.2% biochar at 300 ºC pyrolysis temperature (Konaka et al., 2021). Agricultural feedstocks such as rice straw, rice husk, peanut shells provide a higher yield of biochar (Pandey et al., 2020). Chin-Pampillo et al. (2021) compiled biochar yield data of different agro-wastes such as pineapple stubble, coffee hull, and oil palm fiber which yielded 56, 55.9, and 43.7% biochar at 300 ºC (Chin-Pampillo et al., 2021a). Manure/sludge derived biochar exhibits high pH, increased ash content, and low stability due to the presence of unstable carbon structures (Pandey et al., 2020; Xu et al., 2018). A comparative study for biochar production from various animal manure at 300 ºC showed biochar yield between 39.18-80.96%. The lowest yield of 39.18 and 48.89% was obtained from water buffalo manure and chicken litter, respectively, and the highest yield was obtained from Alpacas and cow manure with 73.10 and 80.96%, respectively (Hossain et al., 2021). Thus, different feedstock types affect the stability of biochar produced in the following descending order viz. woody biomass, agricultural feedstock, and manure waste.

3.2.Moisture content

Biochar properties and yield also depends on the amount of moisture present in the feedstocks. Moisture content is directly proportional to the increased energy and temperature requirement for biochar synthesis (Tripathi et al., 2016; Yaashikaa et al., 2019b). Different types of biomass may contain up to 60% of moisture content. The increased moisture content reduces the rate of heating and simultaneously large amounts of energy and time is required for the pyrolysis process thereby, making the process expensive and inefficient (Tomczyk et al., 2020; Tripathi et al., 2016). For slow pyrolysis, feedstocks with 40-60% moisture were considered suitable for biochar production whereas, for fast pyrolysis, 10% or below moisture is preferred (Pandey et al., 2020).

3.3.Heating rate

The rate of heating is a key aspect of the pyrolysis process as it significantly affects the properties of the biochar produced. Heating rate is defined as the rate of change of temperature or heat. Fast pyrolysis generally requires a high heating rate, which depolymerizes biomass and produces higher liquid (bio-oil) and gaseous (bio-gas) proportions with little biochar formation, whereas slow pyrolysis requires a low heating rate, which protects biomass from breaking down into other residues, resulting in increased biochar yield (Shah et al., 2021; Tomczyk et al., 2020; Tripathi et al., 2016). High heating rates i.e., > 10 ºC/min increase the volatility and porosity, thereby, increasing production of other components and decreasing biochar production whereas a slow heating rate less than 10 ºC/min favours stable structure formation, thereby, increasing biochar yield (Pandey et al., 2020).

3.4.Temperature

Biochar production undergoes thermochemical reactions and therefore, temperature plays a great influence on biochar properties like functional group, surface area, carbon and ash content, etc. (Panwar et al., 2019). The high temperature of pyrolysis results in the production of liquid and gaseous components due to an increase in surface area, pH, and carbon content.

An increase in temperature is directly proportional to an increase in surface area and porosity and surface area of biochar. The increase in temperature increases the surface area and porosity of biochar possibly due to biodegradation of cellulose and lignin components thereby exposing external surface area and pores (Tomczyk et al., 2020).

At high temperatures of approximately 600-700 ^{0}C, biochar has shown more arranged carbon structures and reduced functional groups and at low temperatures ranging from 300-400^{0}C more diverse aliphatic and cellulosic structures are observed. So, high temperatures have resulted in increased carbon content and higher ash content (Tomczyk et al., 2020).

The pH range of biochar has also been reported to rise with rising temperatures. At temperatures above 300 ^{0}C, alkali salts start separating from organic materials, thereby increasing the pH of biochar whereas, below 300 ^{0}C organic components begin to degrade as a result organic acids and phenolic compounds accumulate which in turn reduce the pH value. A constant pH is obtained at temperatures around 600 ^{0}C when all salts are separated (Tomczyk et al., 2020).

Regardless of these characteristics, several more components must be addressed during the biochar synthesis process. Although current pyrolyzers are designed to catch or remove these pollutants, certain phytotoxic and potentially carcinogenic aromatic chemicals such as polycyclic aromatic hydrocarbons (PAHs) and dioxins can be generated during the charring process (Zheng et al., 2018). Furthermore, most biochar may include significant levels of heavy metals originating from feedstocks containing high levels of heavy metals (e.g., sludge, silt, and furfural waste) (Liu et al., 2017a). Unfortunately, hazardous chemicals included in biochar may have negative effects on soil quality, biota functioning, and plant development (Wang et al., 2017a; Zheng et al., 2018). Biochar is predicted to be widely employed in a wide range of settings due to the aforementioned various benefits; as a result, toxicity testing of biochar is desperately required well before the large-scale use as a soil amendment or as an addition for livestock bedding and feeding.

4. Biochar activation approaches and synthesis techniques

Agriculture and forestry businesses have recently started to convert bio-waste into biochar to handle the bio-waste released on a daily basis. According to the reported studies, biochar produced by biomass pyrolysis exhibited less pore density, lean surface functional group, and low surface area (Liu et al., 2015; Manu et al., 2021; Sakhiya et al., 2020). Some applications are restricted due to low specific surface area (200 m^2/g) and porosimetry. To overcome this, the activations of carbonaceous materials involve a carbonization and activation phase (Sajjadi et al., 2019).

Activation is a process that includes raising pore density and specific surface area to improve the absorption capacity and physical characteristics of biochar (Haykiri-Acma, 2006). Basically, there are two methods for activating biochar: physical or thermal activation, in which the pore density increment is initiated by high temperature in an oxidative environment, and chemical activation, in which raw biochar reacts with chemicals (Hydrochloric acid (HCl), Potassium hydroxide (KOH), Potassium permanganate ($KMnO_4$), Hydrogen peroxide (H_2O_2)), resulting in activation at temperatures ranging from 450 to 900 °C, where dehydration and oxidation occur within the biochar and cause the formation of microspores (Sakhiya et al., 2020). In an inert gas environment, partial carbonization (pyrolysis) of biomass and total carbonization of biochar is generally carried out at temperatures between 600 and 900 °C

(Sajjadi et al., 2019). Raw biochar is frequently generated in flue gas or oxygen-limited gas in commercial and laboratory settings. Carbonization eliminates non-carbon species, resulting in biochar with high carbon content. When opposed to traditional biological treatment, the carbonization of biomass has several advantages (Ronsse et al., 2015). Biological processes often take hours rather than days or months, allowing for more efficient and compact reactor design. Furthermore, certain feedstocks are hazardous and cannot be biochemically transformed. Therefore, pathogens and possibly organic pollutants such as pharmaceutically active substances can be destroyed by the high process temperatures (Libra et al., 2011a). Concerning biochar production, the following are some of the most essential and up-to-date activation and synthesis processes.

4.1 Hydrothermal Carbonization (HTC)

Hydrothermal carbonization (HTC) is a cost-effective and beneficial pre-treatment method for converting waste biomass into very dense carbonaceous material that may be employed in a variety of sectors including energy, soil improvement, environment, and nutrient recovery (Maniscalco et al., 2020). This broadens the range of possible feedstocks to include non-traditional sources such as sewage sludges, moist animal manures, aquaculture, municipal solid waste (MSW), human waste, and algal residues (Maniscalco et al., 2020). HTC was also called as wet pyrolysis, and is attracting researchers because of its versatility and, in principle, cheap investment and maintenance expenses (Lucian and Fiori, 2017). To distinguish it from biochar, the solid substance generated during HTC is referred to as hydrochar (Fang et al., 2018). During hydrothermal reactions, the solid material is completely covered by water, which is maintained liquid by using high-pressure reactors that increase with the steam pressure. It's a thermochemical reaction that takes place at temperatures between 180 and 280 ^{o}C and pressures between 10 and 80 bars. HTC has a lower operating temperature because the chemical processes that occur when the biomass is heated in the presence of liquid have lower activation temperatures. Biomass decomposes at high temperatures and pressures through hydrolysis, dehydration, and decarboxylation processes (Volpe et al., 2018a). However, more liquid hydrocarbons are formed (hydrothermal liquefaction) (Gollakota et al., 2018) and more gas was produced (hydrothermal gasification) (He et al., 2014). By eliminating most of the more volatile oxygenated molecules that are normally transported to the aqueous phase, these processes can enhance the carbon content of the original feedstock (Volpe et al., 2018b). During HTC, hydrolysis was the most common process, with lower activation energy than the other breakdown reactions (Libra et al., 2011b).

The ultimate biochar/hydrochar output from HTC is mostly determined by the characteristics of the original feedstock. In reality, the carbon and mineral content of the feedstock, as well as the polymeric structure of the feedstock, will determine the solid matrix's breakdown route. The HTC is recognized to offer numerous advantages over pyrolysis, including decreased energy usage and emissions. Furthermore, as compared to pyrolysis, HTC produces more char while using less energy.

4.2 Template Directed Carbonization

The pore structure of biochar plays a vital role in nutritional element utilization, therefore making greater porosity (mainly micro-mesopores and part of macropores) biochar is very crucial. There are currently no ways for efficiently regulating pore diameter and this pose challenge to fully utilize the bicarbonate structure (Xi et al., 2020). Template based carbonization is a synthetic approach that controls, influences, and modifies the morphology of the material by using the template as the main structure (Yang et al., 2019). The most notable characteristic of the templating approach is its high structural controllability. It controls the size and shape of the material to define its characteristics. The phases in the templating process were as follows: The porous template was first introduced into the biomass feedstock before pyrolysis. Second, the template was removed after pyrolysis, preserving the structure's porosity. The templates are divided into two major categories based on the nature and availability of the template: hard templates that include covalent bond interactions between molecules (Cuong et al., 2019) and soft templates having weak interaction between molecules (Zheng et al., 2021a). The hard template method, also known as the inorganic template method, involves creating a controllable silica gel, impregnating a synthetic silicon template with a monomer or polymer, cross-linking and charring the organic precursor, and removing the silicon template with highly corrosive hydrofluoric acid (Gao et al., 2018a). Aside from that, extra amphiphilic surfactants or block copolymers (P123 and F127) are employed as supplementary templates in the soft template technique also known as organic template, whereas carcinogenic formaldehyde and phenol are unavoidably utilized as precursors (Z. Zheng et al., 2021a). Furthermore, many traditional templating methods used in material synthesis are inapplicable due to the nature of biomass, which includes complicated compositions and low water solubility (Leng et al., 2021). The carbonization temperature needed for the pore structure can be controlled by adjusting it between 400 and 800 °C. However, after significant investment in the technique, the procedures remain cumbersome, time-consuming, and costly. Furthermore, removing the template generally necessitates severe procedures that are not ecologically sound.

Nowadays, in-situ template (self-template) that utilize natural components of biomass is currently a popular research area, because of their impressive results. In 2018, Gao and coworkers used $CaCO_3$ as a self-template and HCl as an etching agent to construct mesoporous biochar from crab shells with 70.80% mesopore and a surface area of 634 m^2/g (Gao et al., 2018a). Similarly, Rybarczyk and colleagues used rice husk to make mesopore-dominant biochar with a surface area of 525 m^2/g, with silicon acting as a template and NH_4HF_2

functioning as a leaching agent (Rybarczyk et al., 2016). However, literature is scarce on the in-situ template technique that strongly proposes investigations based on biomass compositions. In conclusion, most activation techniques favour micropore formation, but templating appears to be a viable option for producing mesoporous/macroporous biochar. As a result, integrating them into the process of making hierarchical porous biochar might serve as an efficient option.

4.3 Microwave assisted Carbonization

Traditional thermochemical conversion methods for recovering value-added bioproducts or biochar from biomass are frequently non-selective and inefficient, so there is a need of an alternative selective, time efficient, cost effective, energy- efficient and appropriate method for the production and activation of biochar from various feedstock biomass with less environmental impact (Foong et al., 2020; Selvamand Paramasivan, 2022). Microwave assisted carbonization is an energy-efficient, cost-effective, and eco-friendly approach that has previously been successfully utilized in biomass pyrolysis for biochar and biofuel synthesis, as well as for the recovery of value-added bioproducts from biomass with minimal environmental impact (Li et al., 2016; Nizamuddin et al., 2018; Yu et al., 2017; J. Zhang et al., 2018a). The mechanism of microwave assisted carbonization is based on dielectric heating (thermal energy that is radiated from the inside to the outside) (Ganesapillai et al., 2016; Gautam et al., 2019), with wavelengths ranging from 1 mm to 1 m and frequencies ranging from 300 MHz to 300 GHz (Gautam et al., 2019). Microwave pyrolysis of biomass produces a product distribution that differs from other types of biomass. The microwave absorbent is preheated to the desired pyrolysis temperature using microwave radiation; then, the biomass waste is pyrolyzed via thermal contact with the microwave absorbent, where the tremendous rate of oscillation between the molecules (millions of times per second) generates heat energy and induces carbonization and volatilization (Foong et al., 2020; Gao et al., 2018; Li et al., 2016; Selvam and Paramasivan, 2022; Zhang et al., 2017). In a summary, the energy is absorbed and conducted to biomass, and subsequently, more carbon was generated from the feedstock while the pyrolysis process continues with microwave activating the processes inside the material, leading to volumetric heating, unlike traditional carbonization. The substantial effect of microwave factors such as power and exposure duration on biochar formation was investigated using a half-resolution factorial design, and it was discovered that these parameters primarily influence product yield. Low power accelerates the carbonization process, but high power not only accelerates syngas production but also improves biochar quality by nearly doubling the proportion in terms of elemental carbon (Lawas et al., 2019). Similarly, the duration of microwave irradiation had a dynamic effect on pore density and surface area. The long-term exposure expands the original pore size and promotes the formation of new pores, whereas severe microwave heating induces pore cracking and loss (Lam et al., 2019). However, microwave is said to be one of the most efficient techniques for generating activated carbon with a greater surface area, which may be employed for dye adsorption in wastewater treatment (Lam et al., 2017). Besides this the microwave pyrolysis or biochar production is also dependent on the microwave absorber (type, particle size, and loading capacity), microwave reactor configuration (output power, mixing, time, and inert gas flow rate), and operation mode (batch and continuous). Biomass is often a low-absorber of microwaves. The presence of high moisture and inorganic compounds, on the other hand, can enhance microwave absorption capacity. At low microwave power, the application of absorbers enhances pyrolysis temperature. Microwave absorbers may heat surrounding biomass particles indirectly, influencing product yield and quality, and they can also function as catalysts, increasing reaction rates by diverging the reaction route and so lowering activation energy (Mushtaq et al., 2015; Zhang et al., 2019). Furthermore, based on prior study, the micropores of microwave-based biochar pyrolysis were consistent and fairly clean, and their surface area is much enhanced. As a result, microwave assisted carbonization may offer a novel method for creating more porous biochar, which may be employed in sorption applications or as a precursor to activated carbon production (Li et al., 2016), and has a wide range of applications including wastewater treatment, adsorption, composting, catalyst, soil conditioner, and energy storage device.

5. Applications of biochar

5.1 Environmental remediation and composting

Over the last two decades, the benefits of biochar on soil amendment and environmental health have been thoroughly researched, with a favourable approach to soil remediation and composting (Table 4) (Godlewska et al., 2017; Wu et al., 2017a). Biochar addition is regarded as an efficient optimization strategy for speeding the composting process and increasing the quality of the final compost due to its unique physicochemical features such as high porosity, recalcitrance, and large surface area (Godlewska et al., 2017). For many years, the use of compost in agriculture and its various short- and long-term contributions to soil quality has been established. Basically, composting is the breakdown, self-heating, and aerobic decomposition of organic waste that may eliminate harmful and poisonous compounds, and the impact improves with time and treatment procedures as compared to other methods (Liu et al., 2021). The amount of waste materials can be decreased by 40%–50% throughout the composting process. As a result, the application of a combination of biochar and compost (end products) to soils has received some attention during the last decade. Despite this, relatively few research have been based on the implementation of biochar into raw materials and its subsequent effect on the composting process, the final combined composted products, and their application to agricultural soils (Antonangelo et al., 2021; Kästner and Miltner, 2016; Wu et al., 2017a; Ye et al., 2019). Although studies focused on the long-term impacts of combined application of biochar and raw material are currently limited, additional study dedicated to analyzing the potential of combined composted products aging in agricultural soils is warranted (Antonangelo et al., 2021; Prajapati et al., 2021).

Biochar, as a compost ingredient, improves composting efficiency and humification, increases microbial species and their activity, lowers greenhouse gas emissions, and immobilizes potentially hazardous metals and organic contaminants associated with compost (Guo et al., 2020a). The temperature rises quicker in the presence of biochar during the composting process, and the thermophilic phase lasts longer. Because biochar has a high water-holding capacity, it meets the fundamental need of 50-60% moisture content at the start of the process (Antonangelo et al., 2021). Aside from that, the carbon to nitrogen ratios (C/N) of different feedstock-derived biochar and composts varies, which has a direct impact on the rate of organic matter decomposition (Godlewska et al., 2017). Composted material contains organic or inorganic nitrogen, which is a valuable fertilizer for crops and essential for the activity of heterotrophic microbes. However, nitrogen loss via denitrification (NOx emission) and ammonification (NH_3 emission) not only produce a slew of environmental issues, such as greenhouse gas emissions and odour, but also reduces the value of end agronomical product (Wang et al., 2021). This restricts the abundance and activity and of heterotrophic microbes, lowering composting efficiency and negatively affecting compostable manure indirectly (Zhang et al., 2021a). Therefore, adding biochar to early composting mixes has been recommended as an effective management approach for reducing nitrogen loss. In the original composting material, a diverse set of biochar ratios from 3 to 50% has been employed, and an addition of about 10% is typically suggested for maximum composting concert (Awasthi et al., 2017; Bello et al., 2020; Liu et al., 2017b; Wang et al., 2017b). In certain studies, biochar has been employed as a filler in chicken manure composting and has resulted in a significant increase in the rate of degradation (up to 70%), as well as a reduction in odour, gas emissions, and nitrogen loss (Dias et al., 2010; Liu et al., 2017b). Furthermore, it has been discovered that combining biochar with compost improves the physicochemical characteristics of the compost and promotes humification while also increasing the pile porosity, favouring O_2 supply and preventing anaerobic fermentation (Xiao et al., 2017). The addition of biochar, on the other hand, can have a variety of effects on the microbial population associated with compost. Biochar can act or provide the space as a home for microbes by sheltering them from dehydration and providing nutrients, as seen in biochar-amended soils (Akdeniz, 2019). The high pore density and water-holding capacity of biochar, as well as its huge surface area and sorption of dissolved organic carbon encourage colonization. Biochar can also provide suitable condition to enhance the microbial growth via aeration of the composting materials, not just as a bulking agent but also due to the micropores within the biochar surface, which facilitates micro-aeration (Akdeniz, 2019; Sanchez-Monedero et al., 2018). Based on the evidence presented above, it can be concluded that biochar addition accelerates composting and improves compost quality and that more nutrients are retained in the compost after biochar addition. Biochar's porous nature can reduce pile density and alter particle size, resulting in improved pile structure and aeration. As a result, biochar is an excellent composting addition choice.

5.2 Catalyst and/or Catalyst precursor

Biochar is a solid carbonaceous precursor to activated carbon produced by extracting oxygen from the thermochemical biomass conversion process. Biochar and biomass supported products such as electricity, value-added chemicals, biofuels and so on are required to overcome the disadvantages of their corresponding fossil based products (Varjani et al., 2017;

Anto et al., 2021; Gunasekaran et al., 2021; Mourya et al., 2021). In this regard, progressing toward a sustainable and carbon-neutral state is critical, which was achieved through the use of chemical, biochemical, and thermochemical processes to produce alternative fuels from biomass (Anto et al., 2021). In fact, the activity and stability of catalysts are critical to the conversion of biomass into value-added products (Yung, 2016). In this regard, many biochar-based catalysts were investigated as competent heterogeneous catalysts for fuel production. Biochar is also known as igneous black carbon that is good and sustainable for the environment (Balajii and Niju, 2019). Its application as heterogeneous catalysts in various biomass conversion processes includes i) tar reduction, ii) gasification for clean syngas production, iii) transesterification for biodiesel production iv) pyrolysis for bio-oil production, v) fermentation for bio-ethanol production, vi) refining for better fuel properties and multiple integrated product recovery (Cheng and Li, 2018; Xiong et al., 2017). Heterogeneous catalysts are more intriguing than homogeneous catalysts because they are simpler to separate, have a greater conversion efficiency, and the chemical reaction happens on their surface (Bohlouli and Mahdavian, 2021). Aside from that, biochar has recently been discovered as a green catalyst for the production of bioenergy in terms of biofuels, and due to its potential, biochar-based catalyst would be a viable alternative to a metal-based catalyst and a carbon catalyst powered by fossil fuels (Guo et al., 2020b; Liu et al., 2015b). Biochar supported catalysts are preferred because they are less expensive, have the capacity to regenerate, effectiveness at high temperatures, capable of continuous operation and have a very good interaction between carbon and metal (Cheng and Li, 2018; Xiong et al., 2017). Various factors such as duration, pyrolysis temperature, transition metals, and the biomass to water mass ratio all have an impact on biochar's catalytic activity to some extent which also needs to be considered during the process. However, many studies have shown that biochar-based catalysts are thermally and physically robust, have a chemically inert, stable structure, and biodegradable with minimal environmental impact, and are used in the production of biofuel from microalgae via biochemical, chemical, and thermochemical routes (Chi et al., 2021; Lyu et al., 2020). As a result, biochar-based catalysts have recently gotten a lot of interest for producing biodiesel from microalgal lipids. The non-graphitizable material/biochar has a high carbon content and is organized with random and irregularly stacked aromatic carbon rings. This is because, even at a high temperature of 2700 °C, biochar cannot be converted to graphitic carbon. Despite the fact that it has a high carbon content, its structure varies from graphite in that the carbon atoms are organized in a 2-dimensional way with parallel stacking, comparable to a planar hexagonal network (Yu et al., 2011). Furthermore, its usage as an electrode material, supercapacitor, soil ameliorant, catalyst, and other applications are dependent on the characteristics it contains from the biomass origin and preparation conditions it undergoes. Therefore, surface area, functional groups on the surface, and matrix nature are all aspects to consider when using biochar as a catalyst (Cheng and Li, 2018). Ren et al. (2014) used maize stover biochar generated by microwave pyrolysis at 650°C to examine the catalytic pyrolysis of torrefied and raw sawdust pellets. The reactor was a batch microwave oven, and the reaction time and temperature were 10 min and 480 °C, respectively (Ren et al., 2014). Their research found that utilizing biochar as a catalyst increased syngas production while also improving bio-oil characteristics. Furthermore, biochar was employed as a catalyst for refining bio-oil in their research. They summarized that increasing the biochar to bio-oil ratio boosted syngas production while decreasing the quantity of coke produced. Several more research on the utilization of biochar as a catalyst for different processes has also been conducted (Lee et al., 2017a). For example, rice husk biochar employed as catalytic support for carbon monoxide (CO) methanation generated 98% methane (Zhu et al., 2015). Biochar was used with base sites to produce biodiesel from waste cooking oil, a 95% biodiesel yield was recorded (Jung et al., 2019). In processes that convert biomass to value-added platform chemicals, biochar has the potential to replace conventional catalytic materials (Y. Lee et al., 2020). As a result, it is a promising candidate for use in biomass conversion processes as a catalyst or support such as gasification, catalytic pyrolysis, and hydrothermal treatments (Gholizadeh et al., 2021).

5.2.1 Heterogeneous catalyst derived from waste

Catalysts are divided into two types: homogeneous and heterogeneous, and they play a vital role in the transesterification process (Behera et al., 2020; Lee et al., 2017a). The most effective catalysts are homogeneous catalysts like CH_3ONa, KOH, and NaOH but they exhibit great difficulty in separation from the reaction mixture and require more water to remove salt and potassium from biodiesel, making them unusable. Heterogeneous (acidic, basic, and enzymatic) catalysts provide several benefits, including quick recovery, minimal corrosivity, reusability, and the lack of a water purification step (Ma et al., 2021; Ramos et al., 2014; Witoon et al., 2014). Metal oxides such as magnesium oxide (MgO), calcium oxide (CaO), and strontium oxide (SrO) are said to be the most common alkali heterogeneous catalysts (SrO) (Chua et al., 2020).

Biomass is a great choice for producing low-cost heterogeneous acid catalysts via a series of processes. These catalysts include polycyclic aromatic carbon sheets with higher density acidic groups and perform admirably in biofuel generation, such as biodiesel, via esterification and transesterification processes (Pandian et al., 2019). Char-based catalysts provide a number of benefits over other catalysts. To begin with, biochar includes trace levels of inorganic metal minerals (K and Fe). These inorganic metal minerals have a unique influence on the biomass pyrolysis process (Wang et al., 2017c). Meanwhile, biochar has a lot of different functional groups on its surface, such as oxygen-containing species (carbonyl groups, phenolic hydroxyl groups, carboxylic groups, and ester groups) or nitrogen-containing species (pyrrole-N, pyridine-N, quaternary-N, etc.) (Chen et al., 2017; Li et al., 2019a). During pyrolysis, the chemical functional groups serve as both absorbents and catalysts (Shen et al., 2015). Biochar-based biodiesel catalysts are classified as solid-acid/alkali supported catalysts. Several studies have found that using biochar as a catalyst during the transesterification process results in high production of biodiesel (Cheng and Li, 2018; Zhao et al., 2017). However, in order for biodiesel to be economically viable, the expenses involved with the transesterification of biomass into biodiesel must be reduced. Previously, it was reported that a biochar supported solid-acid catalyst was created by fuming with H_2SO_4 sulfonation, KOH activation and at 150°C and 1.52 MPa, the transesterification yield of canola oil was 44.2% (Yu et al., 2011). Similarly, at the same 150°C and 1.52 MPa, a biochar supported solid-acid catalyst was also produced for synchronized esterification and transesterification of oleic acid and canola oil combination. In addition, K_2CO_3 functionalized biochar was also utilized as a catalyst for biodiesel synthesis in the same way as KOH. Using a wet impregnation approach, a peat-biochar-supported K_2CO_3 catalyst was produced. When the K_2CO_3 loading was 30% and the activation temperature was 600°C, a maximum of 98.6% biodiesel production was achieved during transesterification phase of palm oil (Wang et al., 2017c). Aside from that, biochar alone and biochar-supported metal catalysts might be utilized to remove tar, which is an essential step in producing clean syngas from biomass via gasification. Olivine, dolomite, , alkali metals, nickel and noble metals are all catalysts for tar cracking (Cheng and Li, 2018).

5.2.2 Magnetic biochar catalyst (MBC)

In the field of environmental remediation of pollutants, biochar plays a vital role in good outcomes. Post remediation the separation from the water was done through several processes including coagulation, sedimentation, clarification and filtration. These are very costly and inappropriate thus limiting the use of biochar as a potential material for water management thereby requiring further improvement (Li et al., 2020a; Rocha et al., 2020; Zhang et al., 2021b).

Magnetic biochar (MBC) catalyst is a form of biochar composite material that has been effectively utilized in the catalytic destruction of organic contaminants as a catalyst, and it preserves the outstanding qualities of biochar (Fig. 2) (Feng et al., 2021; YunQiang et al., 2020), and has been a source of concern in recent years due to its magnetic separation properties. In contrast to biochar, MBC needs to implement magnetic precursors in addition to biomass waste (Niu et al., 2020). Solvothermal, impregnation-pyrolysis, reductive co-precipitation and chemical co-precipitation were the most commonly used MBC synthesis methods (Nidheesh et al., 2021). These methods yield good quality MBC using biomass such as rice hulls, sugarcane bagasse, plant residue, peanut shells with added steel pickling waste liquor as a magnetic precursor (Yi et al., 2019a). Magnetic species have an unavoidable impact on the physicochemical characteristics of biochar. Magnetic biochar, in particular, was excellent for pollutant removal from aqueous solutions due to the combined characteristics of biochar and magnetic material (Ifthikar et al., 2017; Yi et al., 2019b). MBC has been used to reduce pollution in wastewater, soil and gas. MBC, as a good soil improvement, may not only enhance the physiochemical characteristics of the soil but also immobilize or eliminate heavy metals, adsorb and breakdown organic pollutants from the soil (Mandal et al., 2020a, 2020b; Qin et al., 2020; Wu et al., 2020). MBC has been successfully utilized to remove hazardous chemicals from flue gas for gas pollution control (Shan et al., 2019). The removal effectiveness of HgO can surpass 90% when the flue gas temperature is 130 °C (Yang et al., 2019). Similarly, MBC can also function as a catalyst to breakdown organic contaminants in wastewater treatment process (Li et al., 2020a; 2020b). Thus, preparing biomass derived magnetic biochar is a very beneficial approach that not only addresses biochar inadequacies in industrial applications but also expands its applications. For the degradation of organic contaminants, magnetic biochar has also been employed as a catalyst/activator for persulfate and hydrogen peroxide to form highly reactive oxidative species such as sulphate radicals, hydroxyl radicals. For example, it was reported that magnetic biochar and persulfate may effectively degrade the antibiotic ofloxacin (Chen et al., 2018).

Water covers 71% of the Earth's surface, yet only 2.5% of it is fresh and potable; unfortunately, this small amount of water is being polluted and wasted (Li et al., 2020a). Magnetic biochar has been widely used as an adsorbent for cleaning contaminated water and removing tiny particles from water due to its great efficiency in adsorbing contaminants. Following this, the MBC can be separated using external magnets (Li et al., 2017a; Li et al., 2019b; Li et al., 2020a). The magnetic material, persistent free radicals, and other components on the MBC can activate peroxydisulfate (PS), peroxymonosulfate (PMS), and H_2O_2 to form reactive oxygen species (ROS), which can decompose organic contaminants effectively (Huang et al., 2020; Jiang et al., 2019; Kumar et al., 2017; Rubeena et al., 2018). For example, the total organic carbon (TOC) removal efficiency may reach 78.2% and 86.7% respectively, when MBC triggers H_2O_2 to breakdown trichloroethylene and acid red 1 (Yan et al., 2017). When MBC triggers peroxydisulfate to break down 4-chlorophenol, the TOC removal efficacy can reach 63.5 percent, and when MBC is used as a photocatalyst to break down carbamazepine, the TOC removal effectiveness may approach 70 % (Li et al., 2019c; H. Zhou et al., 2020). Several studies have found that the MBC degradation method includes a detoxification mechanism (Kumar et al., 2018; Liu et al., 2019a) that detoxifies the atrazine degradative chemicals produced during the MBC/PMS process (Liu et al., 2020). This shows that MBC may be able to minimize organic pollution by using a catalytic method for degradation as well detoxification.

5.3 Energy storage

Due to the obvious fast growth of population and industrialization, as well as limited energy supplies, demand for biomass as an alternative is rapidly expanding to fulfill the upsurge in the energy demand and to replace fossil fuels (Fu et al., 2021; Mohanty et al., 2018). Biochar has gotten a lot of interest lately because of its cost-effectiveness, energy generation, and low environmental impact. Photovoltaics, hydrogen storage, dye degradation, energy storage devices, and clean up are some more biochar-derived product applications (Balahmar et al., 2015; Blankenship et al., 2017; Jing et al., 2018; Lee et al., 2020b; Li et al., 2018a; Senthil et al., 2019; Sevilla et al., 2018; Tian et al., 2018). In a published study on the thermochemical conversion of biochar by pyrolysis, the energy content of biochar was efficiently increased to a range of 14-30 MJ/Kg, showing tremendous opportunities for energy applications (M. Lee et al., 2020). Biochar undergoes a series of biomass change to yield hierarchical biochar based electrocatalyst for supercapacitors, and it typically retains the distinctive structure of the precursor, such as layered structure, fiber structure and carbon skeleton structure (Wang et al., 2017d; Xu et al., 2020; Zhao et al., 2020). The specific capacitance of supercapacitors may be significantly increased using the double layer electrochemical storage technique by increasing the number of electrode active sites (Chen and Chen, 2019).

Due to its high power density and ability to charge and discharge quickly, supercapacitors have a wide range of uses in hybrid electric cars, electronic gadgets, and medical equipment (Banerjee et al., 2020; Libich et al., 2018). Furthermore, they can aid in the prevention of power fluctuation, that is a key concern for systems involved in converting wind energy (Panhwar et al., 2020). However, commercially accessible supercapacitors have a high production cost and low energy density. As a result, cost-effective devices that are made up of carbon sources that are renewable and workable are needed (Vijayakumar et al., 2018). Recent breakthroughs in the use of biomass-derived carbon materials in supercapacitors had shown the simplicity in boosting the energy density of produced electrodes using various electrolytic processes (Karamanova et al., 2021). Supercapacitors, fuel cells and lithium batteries have all been shown to offer significant promise among the various types of energy storage technologies (Chen et al., 2020a). According to the findings, supercapacitors have greater cycle stability, high power density, and energy density than regular capacitors as well as wide working temperature range, super electric conductivity, and other benefits (Chen et al., 2020b).

Furthermore, the conversion of biomass to biochar and its application as electrodes for ESS are extensively used and have grown in popularity in recent years in order to achieve sustainability and superior electrochemical performances (Senthil and Lee, 2021). In recent years, there has been some interest in the use of biochar to prepare electrodes. Under comparable circumstances, biochar electrodes displayed voltammetric responses similar to those of activated carbon. Biochar has a crucial role in influencing the performance of monolithic biochar electrodes, and it has been observed that biochar may operate as a carrier catalyst in the alteration of biochar-based electrodes manufactured by various procedures (Caguiat et al., 2018; Salimi et al., 2019; Thines et al., 2016). Previously, only woody plants were employed to make one-step moulding biochar electrodes in most research (Chang et al., 2020). Carbon derived materials have been the preferred electrode component for supercapacitors and other devices due to their low cost, availability, and good electrochemical characteristics (Wang et al., 2018b). Since their commercialization, graphite, a crystalline form of carbon, has been a well-known anode material for lithium (Li-ion) batteries, while supercapacitors utilize large surface area carbons as electrodes (Senthil and Lee, 2021).

6. Techno-economics and life cycle assessment in carbon-based catalyst obtainment

Demand for resources and energy has increased as the world's population has grown. The uncontrolled clearing, poor-quality treatment, and unrestricted landfilling of bio-waste, particularly in low- and middle-income countries has resulted in the loss of potential energy sources that could otherwise be utilized to fulfil global energy demands (Gold et al., 2018). It was reported that globally 0.74 Kg of waste was generated per day per person. The global solid waste was expected to rise to 3.40 billion by the year 2050 (The World Bank). Given the multiple applications of coal and bio-waste, assembly costs remain the most major hurdle to thermo-chemical bio-waste energy conversion (Awasthi et al., 2021).

Many techno-economic studies have highlighted the economic elements of biochar production, with the production cost assessed based on the capex and opex costs of conversion methods (Homagain et al., 2016; Jaroenkhasemmeesuk and Tippayawong, 2015; Patel et al., 2016; Sahoo et al., 2019). In recent years, researchers have showed a considerable interest in learning more about the potential, energy balance, and techno-economic assessments of biochar. The enormous potential of biochar to solve a range of environmental problems and enhance the world economy when it comes to energy has resulted in a considerable increase in the examination of this versatile substance. Techno-economic assessment is an integral aspect of every process and its related products' technical and economic performance. Consideration of techno-economic assessment is a method for real execution of the entire system that generally involves process modelling, design engineering, energy balancing, and economic evaluation (Fig. 3). The techno-economic assessment of biochar includes a life cycle carbon footprint analysis, rigorous economic evaluation and energy balance, of the manufacturing process. Energy efficiency is always a significant factor in determining the operation's economic feasibility while evaluating and discussing any process. To analyze energy balance in biochar investigations, the energy yield is defined as the energy generated from the product per unit energy input in the biomass (Weber and Quicker, 2018) and pyrolysis is the most effective and appropriate method for the production of biochar (Kumar et al., 2020). The techno-economic study includes the costs of equipment, biomass/ feedstock collection and manufacture. The cost of collecting includes the cost of labour as well as the cost of transportation. Understanding these expenses (wage, transportation, insurance, and so on) is equally critical. The reactor's power usage is included in the utility bill. Oil or another kind of energy can be used to power it. Heat integration optimization technologies are now widely available, taking advantage of the heat generated throughout the process to save money on energy and ensuring that the cost of operational labour covers all work required during the process (Kumar et al., 2020).

The Life Cycle Assessment (LCA), a well-established and standardized approach, has been frequently utilized to examine the efficiency of biochar systems in recent years, and there is already a considerable corpus of research on the subject (Matuštík et al., 2020). Rather than focusing solely on technical performance and financial expenses, an increasing number of governments and plant managers have recognized and sought to address the environmental sustainability of process systems. The defining of system boundaries is another key part of an LCA investigation. Despite the fact that an LCA is designed to examine a system from cradle to grave (gate), the studies frequently disagree in terms of where the system begins and ends (Matuštík et al., 2020). LCA seeks to quantify the total consequences of energy and materials, as well as to offer information on trade-offs between different impacts throughout the life cycle (You and Wang, 2019).

7. Knowledge gaps and perspectives

Several efforts have been committed to translating biochar for chemo, photo, bio and electrolytic stimulations. In view of the adjacent features of biochar against other pyrogenic designed nano carbons, there is vivid prospective for biochar mediated environmental engineering (Minh et al., 2020). Despite this magnificent progress, a few challenges are remaining which need a direction to forge ahead in future operations. Bioremediation of chemical pollutants in terms of mineralization and detoxification is highly troublesome (Janani et al., 2021). Since the chemical nature of pollutants has its own function and activity, therefore the performance of biochar-based catalysts could also be customized in future investigations (Masek et al., 2018). Self-assembly and refining of building blocks and motifs should be crucial parameters in biochar related structure-reactivity relationships. Upcoming biochar must have strong interfacial charge transfer, biodegradability, and high photo active reactivity. The undeniable release of metals, polyaromatic hydrocarbons, dioxins, furans, and biphenyls from biochar anticipates timely alerts for their controlled scaleup (Bachmann et al., 2016). Leaching these harmful substances into the environment excites potent designs and alternatives that attain future regulatory limits. Intrinsic characteristics of biochar during preparation, operation, and re-use in redox processes need more attention. Because of the complicated interaction between biochar and soil, as well as the inherent contaminants in biochar, not all biochars can achieve good results. As a result, more consideration should be given to the pollutants produced by biochar. Traditional pollutants including VOCs, PAHs, dioxins, and heavy metals, as well as new contaminants like nanoparticles and PFRs, can all be generated during biochar synthesis, according to the existing literature (Han et al., 2022; Zheng et al., 2018). There is currently inadequate evidence in the literature to draw inferences on pollutants in biochar, thus further research is needed to fill in the gaps. First, the quantity and type of contaminants in additional biochars generated from diverse feedstocks and pyrolysis settings should be fully studied. This will aid in elucidating the relationship between feedstock pyrolysis process and contaminant-containing biochar. Similarly, assessing the quantity and structure of contaminants in biochar-based functional materials such as biochar-based nano-composite, magnetic biochar, and composted biochar is highly useful. Furthermore, highly porous and electrochemically active biochar should be favored (Yaashikaa et al., 2020). The potential of biochar as a super capacitor still demands more focus, thus increasing its dimension may lead to good allocation of active sites. To evaluate the economics and environmental influence, a life cycle assessment should also be performed. Characterization of reaction extent and toxicity should be measured by implementing magnetizing biochar which will provide versatile collaboration, configuration, and recovery. However, the efficiency of biochar is mainly depending on the biomass type, thus the biochar should be modelled to advance the technical requirements. Since biochar has evolved as an alternate source for removing contaminants, standard characterization procedures and schemes must be implemented for better understanding and better advancing the progress of this emerging research discipline.

Regarding the efficacy of using biochar in soil applications, there may be a few worries about how it will behave and react in the environment. Studying the fate of biochar in soil and identifying its long-term consequences is critical in order to avoid certain serious environmental problems, such as ecotoxicological effects (Brtnicky et al., 2021; Elliston and Oliver, 2020). Furthermore, the possible human health and harmful consequences of biochar should be extensively explored in order to optimize production circumstances that really can lead to less hazardous biochar, which will safeguard personnel in production facilities and farmers who interact directly with the components. Furthermore, social studies on the general public's perception of biochar use are needed, as well as ways to overcome the constraints that may limit biochar use as a soil conditioner.

8. Conclusions

This review serves an approach for environmental remediation and utilization of waste for the production of environmentally benign and cost-effective biochar. Biochar has offered an efficient way to utilize global waste as a value-added product. It exhibits several potential applications of biochar in composting, as a catalyst & bioremediation agent, and as an energy storage material. Biochar has some disadvantages as it can serve vector for VOCs, PAHs, heavy metals, and dioxins. The techno-economic feasibility and lifecycle assessment of biochar production and utilization has revealed the practical implementation and environmental safety. This study concludes that the utilization of waste derived biochar is economic and eco-friendly which warrants further research on its customization for better efficiency. Understanding processes from socio-economic & environmental view point through LCA would further help in improvement of associated limitations and process sustainability as well.

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Figure Captions:

Figure 1: Schematic representation of waste derived biochar for its potential applications.

Figure 2: Synthesis and application of magnetic biochar.

Figure 3: Framework of life cycle assessment.

Table Legends:

Table 1: Potential uses of biochar and associated benefits

Table 2: Comparative advantages and disadvantages of biochar

Table 3: Factors affecting biochar production and their corresponding yield

Table 4: Applications of biochar in environmental bioremediation

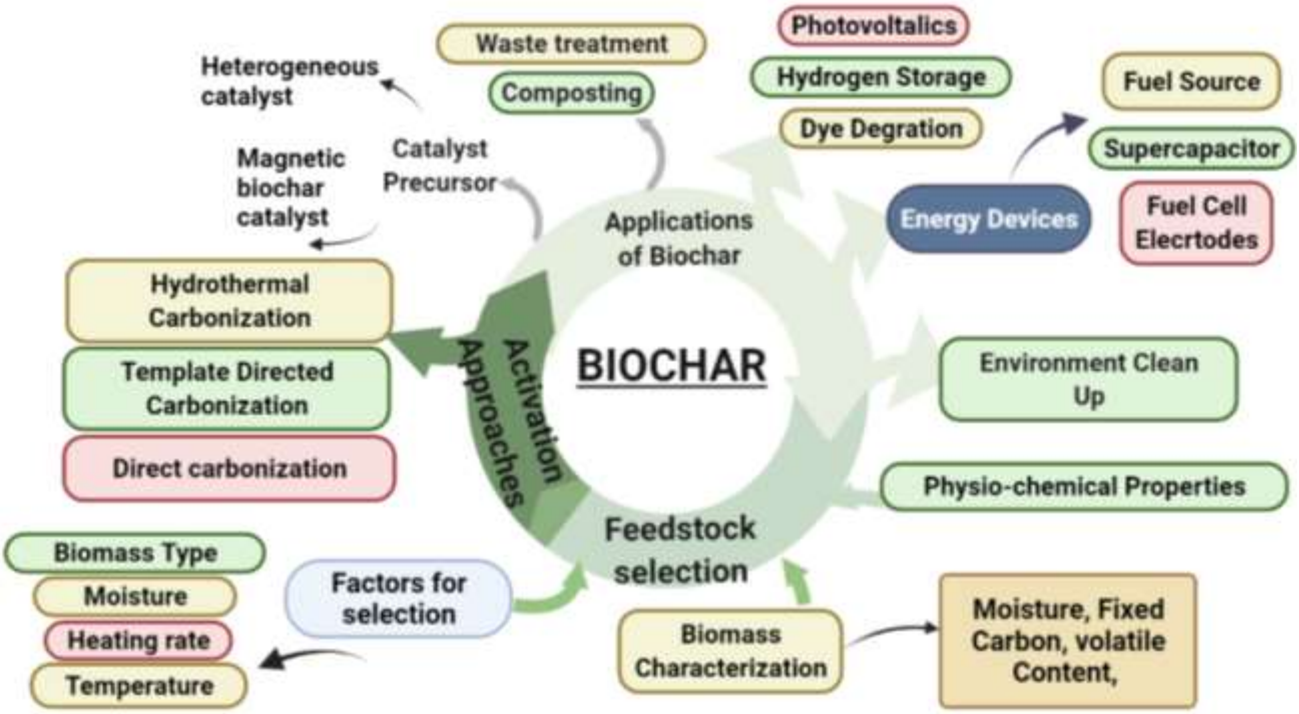

Figure 1: Schematic representation of waste derived biochar for its potential applications.

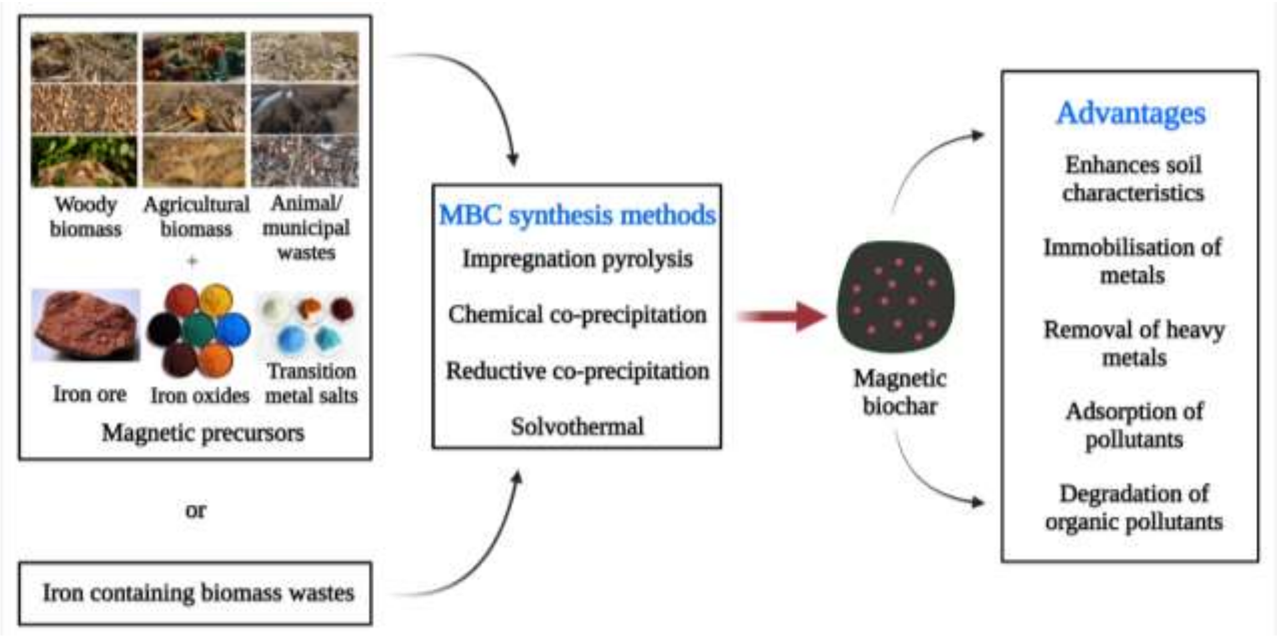

Figure 2: Synthesis and application of magnetic biochar.

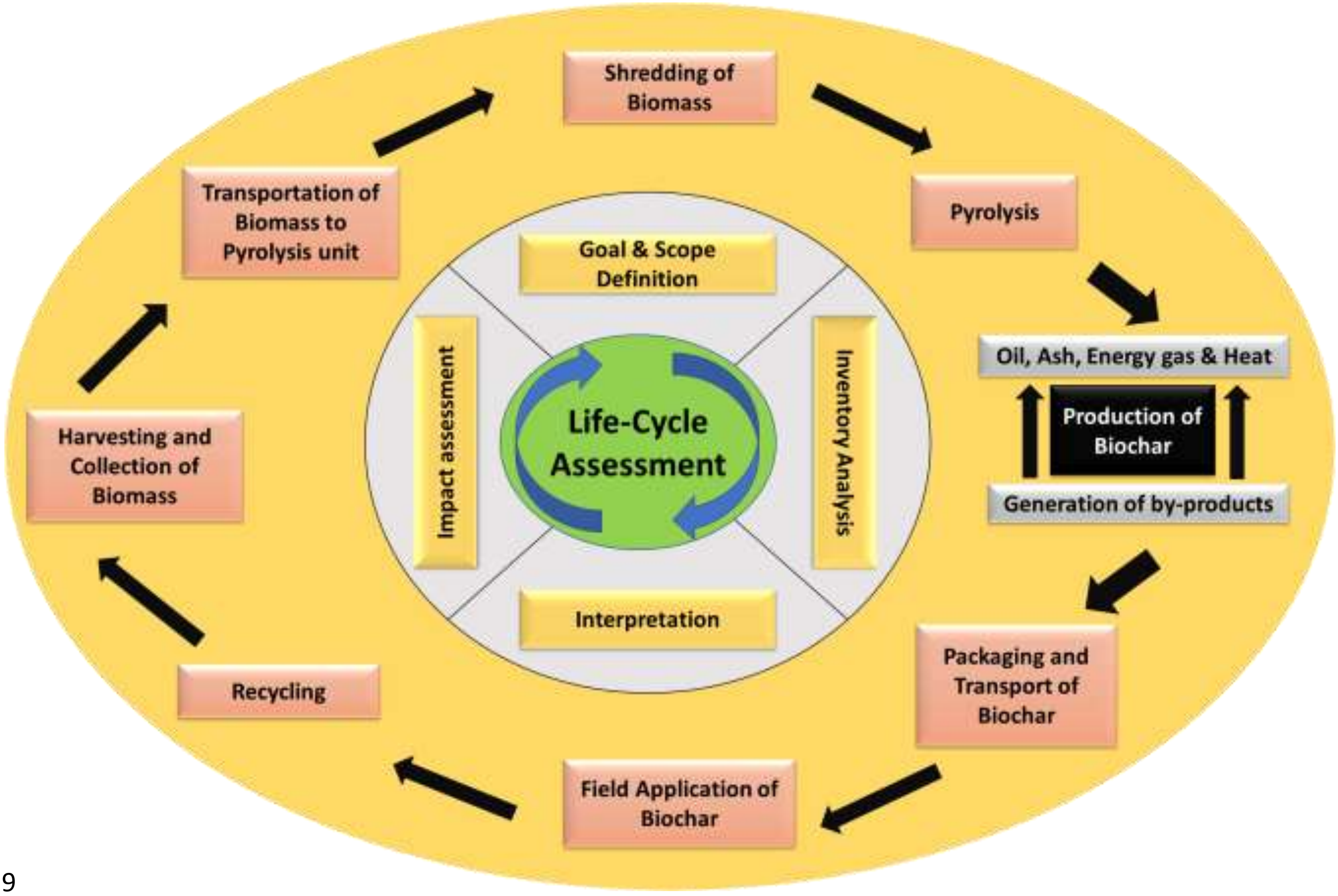

Figure 3: Framework of life cycle assessment.

Table 1: Potential uses of biochar and associated benefits

Sr. No.	**Uses**	**Benefits**	**Reference**
1.	Remediation of Toxic Gas	In the presence of O_2 and moisture, H_2S interaction with alkali biochar surface led to the formation of K, $(Na)_2SO_4$, which might be bioavailable to plants as $SO_4{}^{2-}$ via ionic attraction with COOH and OH groups	(Xu et al., 2014)
2.	Carbon sequestration	Biochar can not only sequester carbon, but also lower the quantity of emitted N_2O, CO_2 and CH_4 in the soil, so assisting in the mitigation of the greenhouse effect	(Kumar and Bhattacharya, 2021; Zhang et al., 2018b)
3.	Microbial proliferation and pollutant biodegradation	The labile soil organic matter (SOMs) on the biochar surface enhances microbial growth and activity, resulting in microbial abundance, activity, and mineralization, which aids in pollutant biodegradation	(Oliveira et al., 2017)
4.	Improving soil health	Biochar minimizes water and nutrient loss by absorbing them, and it can also immobilize soil pollutants that might otherwise endanger biodiversity	(Bolan et al., 2021)
5.	As catalyst for Biofuel Production	Biochar-based materials may also be employed as solid-state transesterification catalysts, and they are especially well adapted to high-purity oils with low free fatty acid concentrations such as biodiesel	(Dhawane et al., 2018; Pathak et al., 2018)
6.	Hydrogen energy	Biochar materials, due to their high porosity and capillarity forces, might be a potential alternative to traditional	(Liu et al., 2019b)

		activated carbon for high-efficiency H_2 adsorption	
7.	Electrochemistry	Biochar made from a range of feedstocks has a high electrical conductivity, making it useful in the electrochemistry sector. It can be used to store energy (batteries) or to create electricity (electrodes)	(Kalderis et al., 2020a)
8.	Waste management	Excess biomass (such as MSW, animal manure, paper mill trash, agricultural waste, household waste and food industry junk) may be utilized to make biochar, which is not only cost-effective but also beneficial since it makes waste more productive	(Kumar et al., 2016; Lee et al., 2017a; 2017b)
9.	Composting process	Biochar's high pore density, large surface area, high cation exchange capacity (CEC), specific functional groups, and adsorption capacity might all contribute to the composting process being more efficient	(Wu et al., 2017a; 2017b; 2017c)
10.	Crop yield	Biochar is widely used in the soil to limit fertilizer release and loss in order to boost crop yield	(Zhang et al., 2018b)
11.	Construction materials	Biochar's qualities, such as low flammability, low heat conductivity, and good stability with chemicals, give it an excellent building construction material	(Gupta and Kua, 2017)

Table 2: Comparative advantages and disadvantages of biochar

Sr. No.	Advantages	Disadvantages	References
1.	Biochar are eco-friendly, economical and improve water holding capacity of soil and prevent soil erosion.	The efficiency of biochar decreased after prolonged usage.	(Srivatsav et al., 2020a; Yang et al., 2019)
2.	Biochar has been found as a possible wastewater treatment option that may also be employed as an adsorbent.	Biochar as an adsorbent can demand further desorption operations, which might result in possible financial consequences.	(Kamali et al., 2022; Srivatsav et al., 2020b)
3.	Biochar adds organic matter, nitrogen, phosphorus, potassium, calcium, magnesium, and other nutrients to the soil, boosting enzyme and microbial activity.	Biochar can act as vector for organic (dioxin and polycyclic aromatic hydrocarbons) and inorganic contaminants (heavy metals).	(Buss and Mašek, 2016; Cheng et al., 2020; Lyu et al., 2016; Zielińska and Oleszczuk, 2016)
4.	Biochar is significant for carbon sequestration and the reduction of greenhouse gas emissions	Under some circumstances, the use of biochar can increase CO_2, N_2O, and CH_4 emissions to a limit	(Liu et al., 2014; Ribas et al., 2019; Yang et al., 2017)
5.	Biochar products have a high heat value with coal, so biochar is an ideal alternative to renewable energy	Generation of associated pollutants due to high temperature and pressure conditions during pyrolysis process	(Cheng et al., 2017; Dai et al., 2019)
6.	Biochar suppresses the activities of plant pathogens (e.g. bacteria, fungi, and viruses), either directly through adsorption or indirectly through gene expression regulation	Biochar can inhibit the efficacy of soil pesticides and their biodegradation effects	(Bolan et al., 2021; Cheng et al., 2017)
7.	Biochar can improve the biological activity of bacteria (e.g., *Geobacter*, *Anaeromyxobacter* and *Clostridium*)	It has a negative impact on the survival, growth and diversity of, for example, acidophilic earthworm and fungi biological communities	(Anyanwu et al., 2018; Chen et al., 2013; Qiao et al., 2018; Wang et al., 2017c)
8.	Biochar alters physical properties of soil, thus increasing soil biodiversity	biochar addition to soil can inhibit plant growth and had a reducing effect on factors such as plant height and leaf width	(Bolan et al., 2021; He et al., 2020)
9.	Biochar efficiently mitigated antibiotic resistance genes (ARG) pollution to some extent in soils and plants	Only selected biochar consistently showed positive effect in mitigated antibiotic resistance genes (ARG) pollution	(Ye et al., 2018, 2016; Zheng et al., 2021)
10.	Biochar can efficiently remove trace metals from Industrial wastewaters like thallium	Face enormous challenges with regard to its large-scale application in the actual environment	(Kalderis et al., 2020b; Selvam S and Paramasivan, 2022)

Table 3: Factors affecting biochar production and their corresponding yield

Biomass type	**Feedstock**	**pH**	**Moisture content**	**Volatile matter**	**Fixed carbon**	**Ash content**	**Pyrolysis temp. (^{0}C)**	**Heating rate (^{0}C/min)**	**Biochar yield**	**References**
Wood biomass	*Acacia cincinnata* trunk *Acacia holosericea* trunk	-	8.12 9.75	74.4 68.98	16.35 19.96	1.13 1.31	500	25	32.41 31.16	(Ahmed et al., 2018)
	Rubber wood sawdust	-	7.13	75.98	15.21	1.68	500	10	23.67	(Shrivastava et al., 2021a)
	Eucalyptus wood Lantana stem Pine needles	8.5-10	8.0 7.2 7.7	75.2 70.5 70.4	14.7 19.8 19.7	2.1 2.4 2.2	450	-	35.5 34.1 29.4	(Chaturvedi et al., 2021a)
	Acacia wood sawdust	-	9.65	68.46	20.56	1.33	400 500 600	25	51.85 35.23 29.72	(Ahmed et al., 2020)
Agricultural waste	Palm kernel shell Empty fruit bunch Palm oil sludge	-	4.53 3.47 5.67	63.01 72.88 28.16	24.91 12.56 23.21	7.54 11.10 42.95	500	-	37.07 35.14 79.16	(Lee et al., 2017b)

	Wheat straw Corn straw Rape straw Rice straw	5.49 5.33 6.15 4.22	-	-	45.53 44.53 44.63 42.12	7.14 6.58 6.95 10.51	300	10	46.96 45.84 44.32 51.36	(Zhang et al., 2020a)
	Wheat straw Corn straw Rape straw Rice straw	5.49 5.33 6.15 4.22	-	-	45.53 44.53 44.63 42.12	7.14 6.58 6.95 10.51	400	10	32.49 33.07 31.17 34.42	(Zhang et al., 2020b)
	Pennisetum purpureum grass	-	5.93	69.44	16.81	7.82	400 500 600	5	35.13 28.41 23.02	(Reza et al., 2020)
	Pineapple stubble Oil palm fibre Coffee hull	6.5 7.0 5.1	70.78 - 5.43	-	42.2 43.9 46.1	11.24 3.86 0.40	300	-	56.0 43.7 55.9	(Chin-Pampillo et al., 2021b)
	Pineapple stubble Oil palm fibre Coffee hull	6.5 7.0 5.1	70.78 - 5.43	-	42.2 43.9 46.1	11.24 3.86 0.40	600	-	34.0 29.6 25.0	(Chin-Pampillo et al., 2021b)
	Oil palm trunk Oil palm fronds	-	7.07 6.48	71.14 71.31	15.42 16.68	6.38 5.24	500	10	25.98 ~25	(Shrivastava et al., 2021b)
	Rice husk Maize straw	8.5-10	7.1 6.5	57.5 60.5	26.7 20.1	8.7 13.0	450	-	31.3 35.2	(Chaturvedi et al., 2021b)

	Sugarcane trash		6.8	59.6	24.6	8.9			31.3	
Municipal waste	Municipal wastewater	-	-	-	16.1	65.3	200 300 500 700	5	94.0 84.5 73.7 70.8	(Fan et al., 2020)
	Sewage sludge	5.5	10.6	50	1.8	39	200 300 600	2.5	90 83 53	(De et al., 2021)
	Cattle manure Spent coffee grounds	9.09 5.05	62 56			36.18 57.25	550	6-7	41.61 21.23	(Stylianou et al., 2020)

Table 4: Applications of biochar in environmental bioremediation

S. No.	**Biomass/ Feedstock**	**Biochar Concentration**	**Temperature (°C)**	**Organic Pollutants**	**Removal Efficiency (%)**	**References**
Soil						
1.	Conifer	0.5 %	600	Phenanthrene	100	(Rao et al., 2017a)
2.	Bamboo	1 %	650	Dibutyl phthalate	87.5	(Qin et al., 2018)
3.	Poplar	0.5 %	600	Pentachlorophenol	100	(Rao et al., 2017b)
5.	Eucalyptus species	0.5%	450	Acetamiprid	52.3	(Yu et al., 2011)
6.	Dairy manure	5%	450	Atrazine	>66	(Cao et al., 2011)
8.	Gossypium species	1%	850	Chlorpyrifos	34	(Yang et al., 2010)
Fresh water						
9.	Chicken manure	0.15 g/L	600	Microcystin-LR	100	(Li et al., 2018b)
10.	Pinus radiata sawdust	2g/L	650	Sulfamethoxazole	100	(Reguyal et al., 2017)
11.	Mangosteen peel	3g/L	800	Methylene blue	80	(Ruthiraan et al., 2017)
12.	Cornstraw	4g/L	500	Atrazine	100	(Tan et al., 2016)
13.	Rice-husk	0.4g/L	500	Tetracycline	90	(Jing et al., 2014)
14.	Soybean Stalk	0.33g/L	700	Phenanthrene	99.5	(Kong et al., 2011)
15.	Waste Douglas fir	0.4g/L	1000	Salicylic acid	100	(Karunanayake et al., 2017)

16.	Sludge	5g/L	550	Gatifloxacin	>90	(Yao et al., 2013)
Wastewater						
17.	Rape straw	1.25g/L	600	Cd^{2+}	100	(Li et al., 2017b)
18.	Sawdust and swine manure	0.4g/L	400	Pb^{2+}	100	(Liang et al., 2017)
19.	Macroalga	0.1g/L	500	Cu^{2+}	80	(Park et al., 2016)
20.	Pinewood	2.5g/L	600	As^{5+}	35	(Wang et al., 2015)
21.	Rice-husk	1g/L	500	Cr^{6+}	100	(Ma et al., 2014)