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Exploring the Benefits of Biochar: A Review of Production Methods, Characteristics, and Applications in Soil Health and Environment

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BIOCHAR is a carbon-rich solid by-product formed by treating biomass to high temperatures in an oxygen-deprived environment. It has recently increased in popularity due to its positive impacts on soils and climate change mitigation among others. Four production processes of biochar have been described in this review; Pyrolysis, Hydrothermal carbonization, Torrefaction, and Gasification. These processes differ in their temperatures, heating rates, usable feedstock, reaction environment, and complexity, ultimately determining the characteristics of biochar produced and their usage. Along with biochar, other products such as bio-oil and syngas are produced in different quantities. The quantities and qualities of these products are based on the temperature of the production process and the type of feedstock utilized respectively. Biochar usage includes and is not limited to soil management, organic waste management, water purification, greenhouse gas emission mitigation, carbon sequestration, fuel alternative, and land reclamation. This review finds biochar extremely important in climate-smart agriculture, mitigating global warming, and contributing a small part to fulfilling global energy needs. The gap in research regarding the effect of biochar from different feedstock needs to be filled, along with the standardization of production methods and application of biochar in various fields to increase the benefits while decreasing the harmful effects on the environment and human health. The research gap can be used as a guide to direct further research on biochar. The production of biochar is seen to have an upward trend, but its adoption by people in agriculture or land management is hindered by the economics surrounding it. Biochar can be an 'environmental savior' but proper policy-making and widespread research and extension must accompany its production.

Keywords: Biochar, Carbon sequestration, Soil amendment, Pyrolysis, Sustainable agriculture, Soil properties, Bioenergy, Biomass management.

1. Introduction

Human intervention is one of the major factors responsible for shaping and drastically changing our environment (Karl & Trenberth, 2003). One of the major reasons for this is the energy crisis which ultimately results in the exploitation of energy sources and their uncontrolled use, resulting in global warming. Energy is imperative for a country's social, cultural, and financial development, in the absence of which the collapse of a nation is imminent (Tainter, 1988). So, in the last few decades, the world's energy consumption, especially across developing countries, has increased and is likely to increase further (Kaygusuz & Bilgen, 2008). To fulfill this requirement, countries have resorted to sources like fossil fuels, hydroelectricity, and nuclear energy among many others. The major energy source consumed worldwide in 2022 accounting for more than 80%, was fossil fuel, mainly oil and coal, which came with its problems (Dale, 2021; Ritchie et al., 2021). According to Friedlingstein et al., (2022), fossil fuel usage is responsible for 89% of anthropogenic CO2 released in the atmosphere. The increased CO2 level in the atmosphere is one of the major causes of global warming and changing climate (Crowley & Berner, 2001), posing a serious threat to agriculture and sustainability globally (Calzadilla et al., 2013). An analysis done by (Lelieveld et al., 2019) showed that an excess mortality rate of 3.61 million people can be

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prevented and an increase of 10-70% in rainfall over certain parts of the world can be achieved by the phaseout of fossil fuel use. There have been many efforts to find a reliable solution to reduce CO2 emissions. One of those solutions is the proper production and application of Biochar (Lehmann, 2007; Stavi & Lal, 2013).

Biochar is a carbon-rich, solid, amorphous end product obtained by heating organic materials in the absence of or a limited amount of oxygen. This process of heating biomass above 250°C is called charring or pyrolysis and is also frequently used in making charcoal (Lehmann & Joseph, 2009). The difference between charcoal, biochar, or any other end product of biomass conversion lies in their use cases and their production techniques (L. Zhang et al., 2010). Charcoal is mainly used as a smokeless fuel source generally used in cooking and heating. When used as a fuel, the carbon stored in charcoal is burnt and oxidized into CO2, so it is not useful for carbon sequestration, unlike biochar. However, if the charcoal is applied in the soil, it acts as a carbon sink and the carbon is stored in a stable form, and it can be referred to as biochar (Hagemann et al., 2018). Many researchers have defined biochar over the years, which has a revolving theme of 'biomass combustion in limited oxygen to obtain a carbon-rich end product' (Hu & Xu, 2019; Sajjadi et al., 2018; Sohi et al., 2010). A standard definition is given by the International Biochar Initiative (IBI, 2013) as "Biochar is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment". Biochar has received increased attention over the past few decades due to its low cost and varying applications in agriculture and the environment (Qambrani et al., 2017; P. Wu et al., 2019). It started gaining attention after it was found to be used as a key component of 'Terra-Preta' soils in the Amazon region which showed an increased crop productivity compared to the surroundings (Fraser et al., 2011). Researchers since then have found plenty of success in using biochar in wastewater cleansing (Pokharel et al., 2020), removal of heavy metals (Q. Wu et al., 2019), carbon sequestration (Sharma, 2018), soil amendments (Vijay et al., 2021), and removal of organic and inorganic chemicals (Biswal et al., 2022). The inherent properties of biochar, cost-effective preparation utilizing otherwise wasteful biomass, environmentally friendly nature, and sustainability in the natural surroundings are what's attracting attention to it (Qin et al., 2020; Yaashikaa et al., 2020).

The main aim of this paper is to compose, compile, organize, and summarize the scattered information and researches regarding biochar. This review describes biochar, its properties, production techniques, and its application in soil health and the environment. Several comparisons have been made between the production techniques, materials used, and methods of application. This review also aims to provide a clear understanding of biochar's creation, functioning, and varied usage, along with highlighting the gaps in research and the need to fill them. The audience can expect to have a general understanding of why and how biochar is made, the working of biochar in soil, its effects on the environment and the potentiality of biochar in preserving and improving soil health.

2. Biochar production methods

Biochar can be prepared from a wide range of organic sources, which are mentioned in Table 1. There are mainly 4 methods of biochar preparation depending on the process, end product, apparatus, and temperature during preparation; Pyrolysis, Hydrothermal Carbonization, Dry torrefaction, and Gasification (Kambo & Dutta, 2015) (Fig. 1).

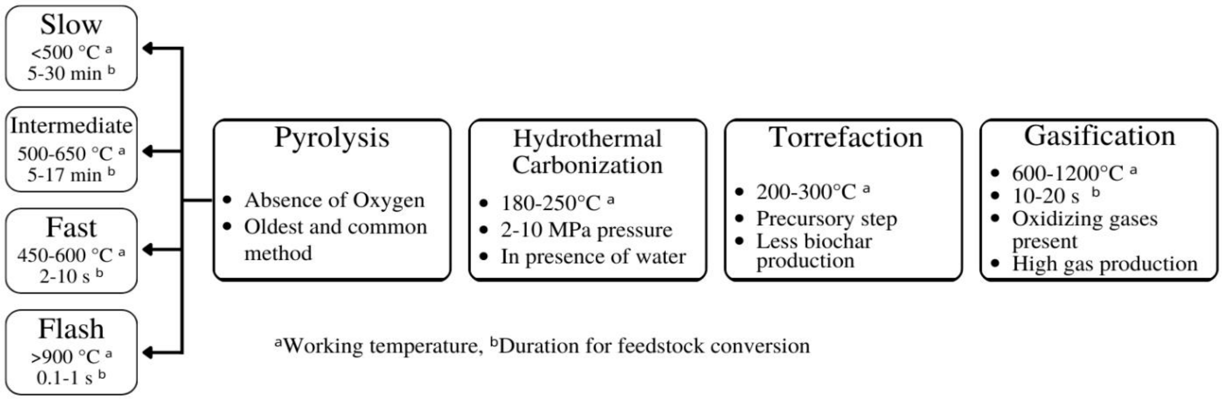

Fig. 1. Overview of production techniques of Biochar.

Table 1. Overview of feedstock used, pyrolysis process, temperature, heating rate, yield, and nutrient content of biochar.

S.N.	Feedstock	Pyrolysis Process	Temp °C	Heating Rate °C/s	Biochar Yield (%)			Nutrients %			Reference
					Bio-oil	Biochar	Syngas	N	C	O	
1	Pinewood Chips	Slow	500	-	30	58	12	-	-	-	(Sakhiya et al., 2020)
2	Rice Husk, Rice straw, Empty fruit bunch	Slow	500	-	26-38	47-54	13-20	-	-	-	
3	Woodchips	Slow	500	-	18	59	23	-	-	-	
4	Rice Husk, Peanut Shell, Cassava stalk, Switchgrass	Slow	450	-	15-25	32-35	12-19	-	-	-	
5	Dairy Manure	Slow	350	25.0	-	-	-	2.2	25.2	-	(Qambrani et al., 2017)
6	Miscanthus	-	300-600	10.0	-	53.8	-	0.3-0.4	68.5-90.7	25.7-6.7	
7	Sow Manure	-	300	26.0	-	60.0	-	2.9	38.4	11.7	
8	Peanut shells	-	700	7.0	-	57.6	-	3.9-4.1	84.2-90.1	6.48-8.14	
9	Walnut shells	Fast	600	-	-	-	89.88	-	89.88-90.79	6.48-8.14	(Yuan et al., 2019)
		Flash	800-1200	-	-	60	40 (gas+oil)	-	-	-	
10	Apple Wood	-	700	-	-	22.6	-	0.7	93.6	-	(Kinney et al., 2012)
11	Magnolia leaf	-	500	-	-	31.9	-	1.2	51.6	-	
12	Coconut Husk	Slow	140	34.9	-	>75	-	-	-	-	(Chi et al., 2021)
13	Watermelon peel	Slow	260	216	-	54	-	-	-	-	
14	Wastewater sludge	Slow	300	-	-	72	-	3.3	25.6	8.3	(Gaskin et al., 2010)
15	Sewage sludge	Slow	200	-	-	-	-	4.0	28.4	21.3	
16	Pinewood chips	Slow	300	-	-	61%	-	-	63.9	30.4	
17	Oxytree Prunings	Slow	200	-	-	98%	-	4.6	38.1	42.4	
18	Microalgae	Slow	500	10	-	37	20	-	-	-	(Lee et al., 2020)
19	Saccharina japonica	Fast	300-500	-	33.0-33.2 MJ/kg	11.8-12.4 MJ/Kg	-	-	-	-	
20	Chlorella	Fast	500	-	24.8-28.3 MJ/kg	-	4.60-12.9 MJ/kg	-	-	-	
21	Sewage sludge	-	300	-	-	83.3	-	61.2 g/kg	-	-	(Yuan et al., 2015)
		-	700	-	-	65.0	-	9.1g/kg	-	-	
22	Straw	-	600	-	-	30.89	-	0.77	60.08	10.62	(Zhang et al., 2014)
23	Lignosulphate	-	600	-	-	43.85	-	2.95	36.81	36.81	

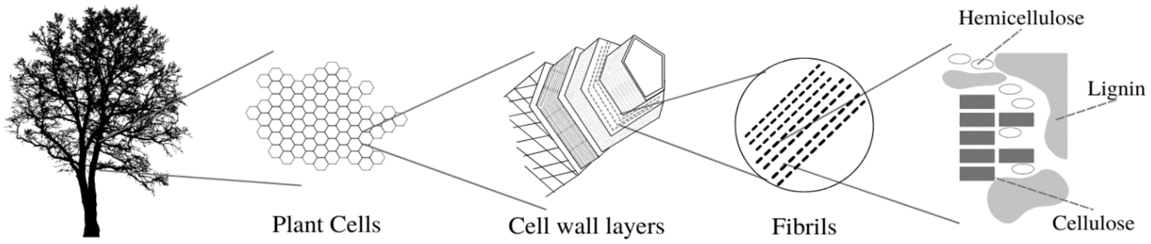

Fig. 2. Structural composition of plant biomass Pyrolysis.

The preparation of biochar from biomass occurs by phasic reactions of cellulose, hemicellulose, pectin, and other compounds present in organic substances, especially of plant origin as shown in Fig 2, generally in the absence of or limited oxygen in high temperatures (van der Stelt et al., 2011). With the rise in temperature, dehydration, cross-linking, depolymerization, fragmentation, rearrangement, repolymerization, condensation, and carbonization occur at different levels of temperature (Masebinu et al., 2019), producing syngas along with condensed carbon structure called biochar and liquid bio-oil (van der Stelt et al., 2011). The proportions of the products change with production techniques and variables during the process.

Pyrolysis is a thermochemical process of conversion of biomass at a temperature of 200-900°C and limited or absence of oxygen (Jeyasubramanian et al., 2021). It is one of the oldest methods of biochar preparation (Chi et al., 2021) which has many models of production modified according to the needs of people. One of the mobile models for biochar production used locally has been shown in Fig 4. Based on the temperature, duration, and heating rate of pyrolysis, it can be divided into four methods: Slow, Intermediate, Fast, and Flash (Al-Rumaihi et al., 2022; Armah et al., 2023).

Slow pyrolysis is carried out at a temperature below 500°C with a low (5-7°C/min) heating rate with the main product yield of solid biochar (Canabarro et al., 2013; Amini et al., 2019). The biomass is kept for a longer duration in the reactor between 5 to 30 minutes (Masebinu et al., 2019). It is available in batch, semi-batch, and continuous systems and the most common and useful method used on small a scale is the batch method (Gustafsson, 2013). In this process, the vapor isn't allowed to escape but rather is kept in the container to permit secondary reactions which allow extra char production and a lesser amount of bio-oil and syngas (Canabarro et al., 2013). Slow pyrolysis is more resilient towards biomass with higher moisture content and useful for greater amounts of biomass than the other two pyrolysis methods since heat is transferred evenly creating less gradient and less differentiation in occurring reactions (Brownsort, 2009; Kim et al., 2019). Bio-oil obtained from slow pyrolysis using a mobile biochar stove has been shown in Fig 3 and Fig 4 respectively.

Intermediate pyrolysis is carried out between temperatures of 500-650°C for 5-17 min with heating rates of 0.1-10°C in the reactor (Al Arni, 2018). Bio-oil (~55%) is the main product derived from intermediate pyrolysis followed by syngas and biochar (Dasappa, 2014; Armah et al., 2023).

Fast pyrolysis is a quick way of decomposing biomass in temperature ranging from 450-600°C for 2-10s (Dhyani and Bhaskar, 2018; Armah et al., 2023). The products of fast pyrolysis typically consist of 50-70% bio-oil, 10-30% biochar, and 15-20% syngas (Laird et al., 2009).

Flash pyrolysis has the shortest residence time among all the pyrolysis methods. The temperature ranges around and above 900°C and the residence time of biomass is between 0.1 and 1s (Demirbas and Arin, 2002). The main products from flash pyrolysis are bio-oil followed by smaller amounts of biochar and syngas (Chisti, 2019).

Fig. 3. Bio-oil obtained from slow pyrolysis.

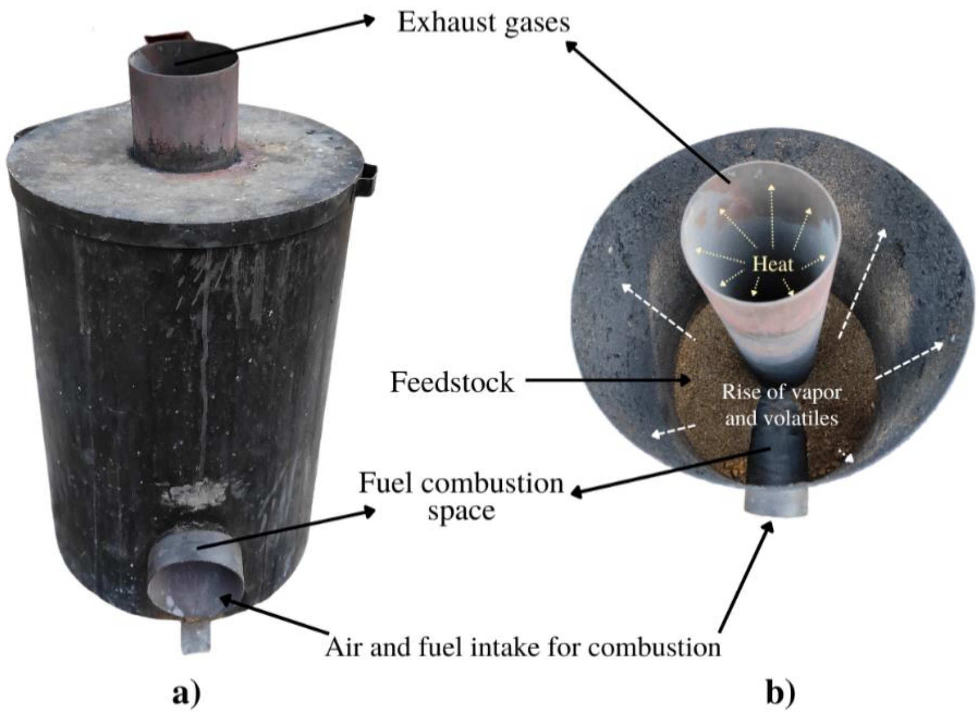

Fig. 4. Typical mobile domestic Pyrolysis stove, a) Front View, b) Top-Down View.

2.2. Hydrothermal Carbonization

Hydrothermal carbonization (HTC), also called wet torrefaction, wet pyrolysis, and artificial coalification is a thermochemical process of conversion of biomass into carbon-concentrated solid or sludge-like products (Wang et al., 2018; Zhou et al., 2019). Unlike dry pyrolysis, it is done in the presence of water as shown in Fig 5, and at a temperature ranging from 180-250°C and a pressure of 2-10 MPa (Mumme et al., 2011). Primarily, hydrochar is formed along with some gases (mainly CO_2) and liquid, whose proportions are dependent upon the temperature and biomass used. It produces less gas compared to dry pyrolysis and has a high total conversion of carbon to the final product (40-70%) (Yan et al., 2010). Since the reaction takes place underwater, there is no need for pre-drying of biomass, which is a necessary step in dry pyrolysis. This allows HTC to utilize a wide range of biomass as feedstock and helps in saving energy in drying (Benavente et al., 2015). However, a large volume of water (3:1 water to biomass) is required for the process, making it unsustainable in the long run unless a recycling system is used. The hydrochar particles have a high concentration of surface oxygen groups, making them less likely to flame by themselves as compared to biochar, but comparatively, hydrochar has less surface area and porosity (Kambo and Dutta, 2015). After the formation of final products, they are subjected to mechanical as well as thermal dewatering for further use (Mensinger, 1980).

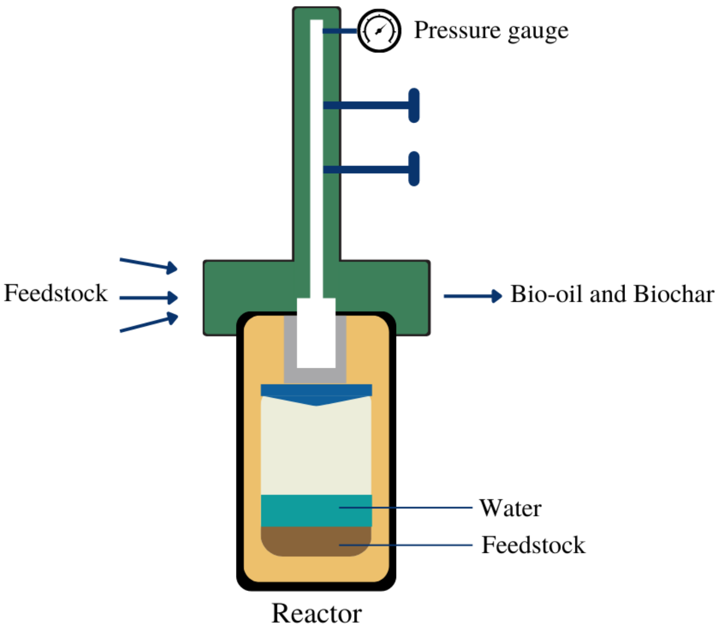

Fig. 5. Diagrammatic illustration of Hydrothermal Carbonization reactor (Du et al., 2019).

2.3. Torrefaction

Torrefaction is the process of thermal pre-treatment of biomass at relatively low temperatures of 200-300°C in the absence of oxygen. The process can also be referred to as mild pyrolysis, roasting, high-temperature drying, and wood cooking (van der Stelt et al., 2011). Torrefaction is a step for further processes of biomass whether that be gasification, combustion, storage, or transport. The process releases CO_2, moisture, and some volatiles from the biomass which ultimately results in decreased oxygen and an increment in the energy density of biomass since a 30% weight reduction only reduces 10% of the available energy in the biomass (Bergman et al., 2005; Prins et al., 2006). The removal of smoke-generating compounds from the product makes it even better for combustion and gasification in the future. Pentananunt et al., (1990) have shown that the torrified wood had an increased combustion rate than normal wood and reduced smoke when combusted. However, the removal of volatiles and gases is incomplete since it is at a low temperature and just at the beginning phase of pyrolysis. The resulting product possesses characters in between raw material and biochar therefore the final product cannot be called biochar (Kambo and Dutta, 2015). The mild heat treatment decays the fibrous structure of biomass decomposing hemicellulose present and creates a hydrophobic product that is easier to grind and use for further processes (Arias et al., 2008; Brewer et al., 2009). The hydrophobicity of the new biomass is useful in the storage of wood and other biomass since it declines the rotting possibility (van der Stelt et al., 2011).

2.4. Gasification

Gasification is a thermochemical conversion of biomass into various gases and hydrocarbons at a high temperature ranging from 600-1200°C for a short duration of 10-20s. There is some presence of oxidizing gases like oxygen, CO_2, steam, Nitrogen, or their mixture during gasification (Brewer et al., 2009; Prabakar et al., 2018). The partial oxidation of biomass converts the energy available in biomass into gaseous form (Maitlo et al., 2022). The conversion and further combustion are much more efficient for materials with a low O/C ratio, which can be obtained via torrefaction (Puig-Arnavat et al., 2010). Syngas (~85%) is the main product of gasification with a small amount of biochar (~10%) and liquid products (~5%) (Armah et al., 2023). Ideally, no residual char is formed which isn't the case in normal practice. The main gases formed from the process include H_2, CH_4, CO, and CO_2 which are further used as gaseous fuels and are much more efficient and easier to use than raw biomass. The little biochar formed by gasification shows stability, and resilience against chemical oxidation (Puig-Arnavat et al., 2010; Jeyasubramanian et al., 2021). However, the biochar produced usually has a higher concentration of alkali and alkaline earth metals and Poly Aromatic Hydrocarbons (PAHs). These elements and compounds are toxic compounds produced due to the high working temperature of gasification (Ippolito et al., 2012). So, it limits the use of the biochar until further processing is done and renders the gasification process to just the production of gaseous fuels. A schematic process of gasification has been shown in Fig 6.

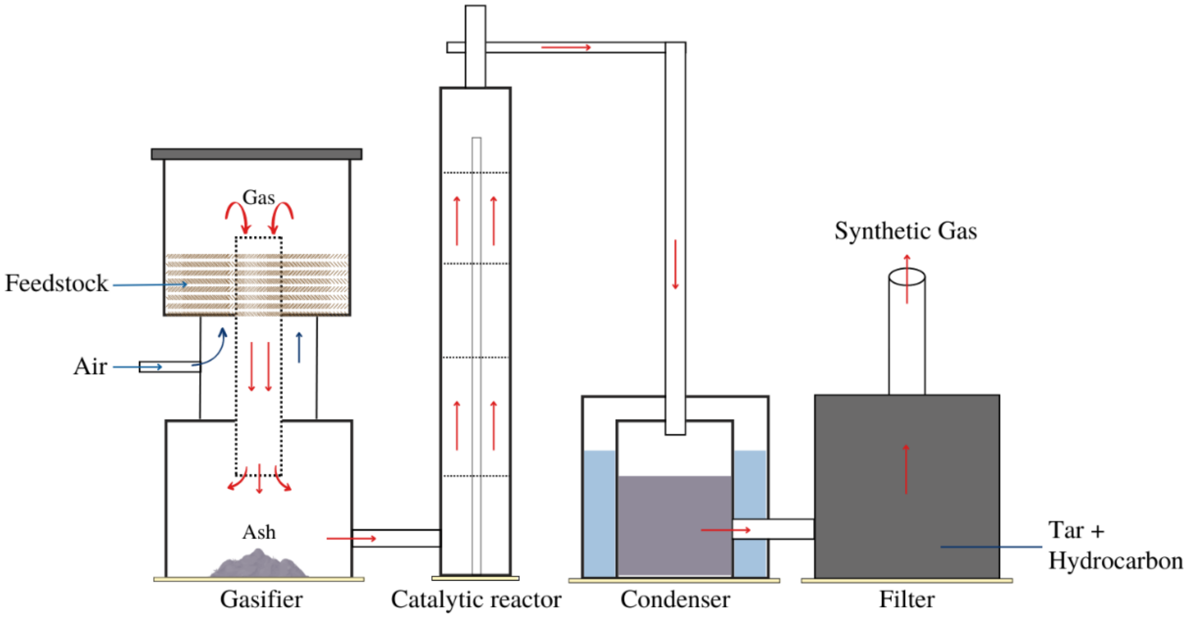

Fig. 6. Schematic illustration of the Gasification process (Dechapanya et al., 2020).

3. Characteristics of biochar

3.1. Physical Characteristics

Biochar is a product with multidimensional physical and chemical characteristics (Chia et al., 2015). Preparation temperature and parent material govern biochar properties, and the treatment methods enhance its characteristics (Tang et al., 2013). This section summarizes the following physical properties: Surface area and poor size, Hydrophobicity and field capacity, structure, Thermal conductivity and heat capacity, mechanical stability, density and porosity, and grindability.

3.1.1 Surface area (SA)

The pore structure and development of pores in biochar are determined by the biochar production technique, dehydration process, and volatile release mechanism of biomass (Bagreev et al., 2001). The overall usage and effectiveness of biochar for the sorption of compounds are dependent upon the porosity and surface area. The efficacy of the herbicides in the soil is negatively impacted by the high surface area of biochar incorporated in the soil (Graber et al., 2012). Surface area maximization is highly applicable for media (water and beverage) filtration. The wet-milling with a planetary ball mill maximizes the surface area of biochar (Peterson et al., 2012).

3.1.2 Hydrophobicity and Field Capacity

Production condition determines, among various other properties, the hydrophobicity of biochar, which alters soil's hydrological properties. Change in field capacity can be observed, increasing with the increase of hydrophobicity of applied biochar (Zornoza et al., 2016). Gray et al., (2014) also concluded the importance of the selection of appropriate feedstock while producing biochar to create sufficient porosity and maintain the appropriate temperature to reduce hydrophobicity, which increases the water-holding capacity of the soil by repelling water from biochar in soil. The water uptake (sorption) by biochar relies upon its porosity and hydrophobicity (Singh Yadav et al., 2023) and there are ways to increase it. Controlled pyrolysis temperature from 400°C-600°C gives biochar with peak field capacity and minimum hydrophobicity (Kinney et al., 2012).

Fig. 7. Hydrophobicity showed by ground Rice-husk biochar.

3.1.3 Structure

Pre- and post-treatments of feedstock and resulting product determine the biochar structure, eventually influencing its physical characteristics. Precursors variation and different pyrolysis parameters (e.g., heating temperature, heating rate, residence time) result in diversity in biochar structure (aliphatic, aromatic, and defective) (Zhang et al., 2020). Biochar differ in their morphology; resulting in spherical, tubular, nano biochar, graphitized, and chemically functionalized biochar (Qin et al., 2020). Low temperature during production results in increased aliphatic structure while the increase in temperature enhances the formation of graphite structure (Zhang et al., 2021a). K. H. Kim et al., (2012) obtained a highly aromatic carbon structure biochar of pitch pine (Pinus rigida) upon pyrolysis from 400°C – 500°C.

3.1.4 Thermal conductivity and Heat Capacity

Thermal properties of biochar are altered by drying, the conversion process of biomass, and combustion. Biochar properties are highly dependent on feedstock, process conditions, and environment. Biochar has self-heating and spontaneous combustion properties due to the presence of highly volatile matter in untreated biomass (Weber and Quicker, 2018). Thermal conductivity is influenced positively by the direction of heat flow, and density and negatively by porous structure (Weber and Quicker, 2018) and the low thermal diffusivity of biochar leads to the reduction in soil thermal diffusivity (Zhao et al., 2016). Biochar application has the potential to regulate the soil's thermal properties like thermal conductivity, heat capacity, and thermal diffusivity (Usowicz et al., 2016).

3.1.5 Mechanical stability

Mechanical stability influences biochar handling, transport, and storage. Biochar's mechanical stability (abrasion, resistance, friability, tensile strength) is lower than the parent biomass (Weber and Quicker, 2018). The mechanical strength of biochar is directly correlated with density. Feedstock with a high density and high lignin content produces biochar of high compressive strength. The slow heating rate and low moisture content of feedstock lead to the production of biochar with higher strength (Kumar et al., 1999). The increment of biochar incorporation into neat polypropylene biocomposite improves tensile and flexible strength and also reduces heat release and smoke production from bio-composites (Chia et al., 2015).

3.1.6 Density and porosity

Density serves as a property for the design and operation of all handling and processing facilities for any bulk materials. Biochar application has a significant effect on soil physical properties, particularly immediate effects can be seen in soil bulk density and porosity. Aslam et al., (2014) and Githinji (2014) reported a linear decrease in soil bulk and particle density and an increase in soil porosity and infiltration rate by application of biochar. Biochar's skeletal and envelope density, and porosity, increase with an increment in pyrolysis temperature and use of biomass feedstock respectively (Brewer et al., 2014).

3.1.7 Grindability

Carbonization of biomass leads to the formation of brittle char which has increased grindability as compared to raw biomass. Biochar grindability can be determined by Hardgrove Grindability Indices (Weber and Quicker, 2018). Biomass treated with low temperature and untreated biomass shows low grindability (Bridgeman et al., 2010). The difference in grindability of biochar in relation to its parent material increases drastically up to a pyrolysis temperature as low as 300°C but a further increase of pyrolysis temperature up to 500°C only leads to a small increment (Abdullah and Wu, 2009).

3.2. Chemical Characteristics

Chemical properties of biochar help to determine its application in the soil. The chemical properties of feedstock from raw to biochar production vary with the pyrolysis period and condition (Evans et al., 2017). The physicochemical properties of biochar from different precursors are affected by a combination of heating temperature (200°-700°C), residence time (1-8 hours), heating rate, and atmosphere (Air-flow, Presence/absence of air and N_2) (Luo et al., 2015).

3.2.1 Elemental Composition

The chemical composition of raw biomass changes during biochar preparation. There is an increase in fixed carbon content which is due to the detachment of functional groups containing oxygen and hydrogen (Weber and Quicker, 2018). Agricultural residues of corn cob have the highest amount of C (81.35%) and H (2.42%) and also stable C and low H/C ratios are observed under slow pyrolysis (Wijitkosum and Jiwnok, 2019). The total elemental content of C, N, P, K, Ca, and Mg increases while the total content of O, H, S, and unstable forms of organic C and acid functional groups decrease when pyrolysis temperature increases from 200°C to 800°C (Al-Wabel et al., 2013).

3.2.2 Energy Content

Biochar is considered an exceptional bioresource for energy. Rise in temperature, and prolonged residence time have a positive effect on energy content increment. Biochar treated at a temperature range between 250°C and 350°C undergo a raise in heating value from 20MJ/kg to 25-30 MJ/kg while at 700°C reaches up to 30-35 MJ/kg (Weber and Quicker, 2018). Lignocellulosic biomasses from agriculture (eg. corn, stover, corn cob, bagasse, straw, stalk husk, etc.), forestry (eg. woodchips, sawdust, insect-infested wood, etc.) and grasslands (eg. switchgrass, timothy grass, elephant grass) pyrolyzed under controlled operating conditions produce energy-dense solid, liquid, and gases in which chemical energy from biomass is retained (Nanda et al., 2016).

3.2.3 Fixed carbon and volatile matter

Feedstock source and pyrolysis temperature determine biochar's final composition. Fixed carbon remains when volatile compounds are driven off a solid structure. Devolatilization and a decrease in volatile matter result in an increment of fixed carbon at a temperature of 700°C (Weber and Quicker, 2018). The presence of more than 20% ash causes a decrease in fixed carbon content whereas the increasing combination of volatile matter and H:C ratio improves biochar stability (Enders et al., 2012). Fixed carbon content in biochar highly depends on the intensity of thermal treatment. X. Yang et al., (2020) reported a temperature of 500°C, a heating rate of 4°C/min, and a holding time of 120 minutes as an appropriate carbonization technique for producing biochar with high fixed carbon content from pruned apple branches.

3.2.4 pH and Cation Exchange Capacity (CEC)

Biochar is one of the best remedies to global soil acidification for improving soil properties and reducing hazards caused by soil acidification (Kochian et al., 2015; Dai et al., 2017). Biochar physiochemical properties vary highly due to feedstock selection and pyrolysis. The pH of manure-based biochar is higher than lignocellulose-based ones (Dai et al., 2017). The alkaline nature and high buffering capacity of biochar are responsible for soil acidity correction. Chia et al., (2015) found the average pH of biochar to be 5.01 and 9.00 at 300-399°C and 600-699°C respectively.

Pyrolysis of biomass produces biochar which is negatively charged; thus, contributing to the adsorption of cations. Biochar produced with low temperatures, depending upon the biomass used, typically has increased surface area, leading to higher cation exchange capacity (Weber and Quicker, 2018). Biochar surface oxygenation by ozonization and Ammonium Acetate (NH_4OAc) method are effective for increasing the cation exchange capacity to enhance soil productivity (Munera-Echeverri et al., 2018; Kharel et al., 2019). The CEC of soil is increased due to carboxyl groups formed by the oxidation of aromatic rings present in biochar (Glaser et al., 2002).

3.2.5 Functional groups and reactivity

The thermal decomposition of biomass during carbonization detaches functional groups and releases hydrogen and oxygen. The high degree of carbonization results in the production of biochar with fewer functional groups and more aromatic structure (Conti et al., 2014). The high thermal stability, because of the aromatic structure is important for soil amendment and metallurgical purposes (Weber and Quicker, 2018). The transition of carbon-rich functionalities over oxygen-rich functionality results in the dominance of aromatic structure, eventually significantly increasing the hydrophobicity of biochar (Fan et al., 2022). The reactivity of char influences any biochar application involving thermochemical conversion of the material. Boudourd reaction, water gas reaction, and oxidation of carbon can describe the conversion of the char.

$$C + CO_2 \longrightarrow CO_2$$

$$C + H_2O \longrightarrow CO + H_2$$

$$a.C + b.O_2 \longrightarrow c.CO + d.CO_2$$

The reactivity of these reactions depends on the temperature and the concentration of the reactive gases (Weber and Quicker, 2018). The indigenous alkali metals with adequate surface area affect the gasification reactivity of char (Duman et al., 2014).

4. Factors affecting Biochar qualities

4.1. Temperature

The temperature during pyrolysis generally ranges from 100°C up to 1000°C depending upon the type (Ahmad et al., 2014), and it drastically affects the overall outcome of the biochar obtained. The differences between biochar prepared in high and low temperatures can be found in their structure, chemical properties, and interaction with other materials during use. Cantrell et al., (2012) showed that higher pyrolysis temperature results in an increased surface area and greater microporosity. This increases the adsorption capacity of high-temperature produced biochar than the lower temperature (Elbasiouny et al., 2023; Kołodyńska et al., 2012). An analysis done by Chun et al., (2004) showed that wheat residue resulted in well-carbonized and greater surface area (>300 m^2/g) biochar at 500-700°C whereas a partially carbonized and lower surface area (<200m^2/g) biochar at 300-400°C. However, results of biochar having decreased porosity in higher temperatures have also been obtained in rice straw and canola stalk biochar (Yang et al., 2021), and Crofton weed biochar (Fan et al., 2019), suggesting that the porosity is more dependent upon the type of feedstock used than the temperature during biochar production.

Pyrolysis in higher temperatures occurs in three phases; Pre-pyrolysis (<200°C), where there is a loss of water and volatile compounds, Main-pyrolysis (200-500°C) with degradation of cellulose and hemicellulose, and Carbonaceous substance formation (>500°C), where stronger and stable compounds like lignin and resins are decomposed (Cárdenas- Aguiar et al., 2017; Tomczyk et al., 2020). The continuous decomposition of compounds (cellulose, hemicellulose, lignin) along with the creation of amorphous carbon structures creates micropores (Zhao et al., 2017). The release of volatiles and the formation of micropores increase the porosity as temperature increases up to a certain level (Shaaban et al., 2014). As the temperature rises most of the organic matter volatilizes, leaving the inorganic minerals as residue. So biochar prepared at higher temperatures is rich in ash and elemental nutrients like P, Ca, and K (Buss et al., 2016). Liberation of alkali salts from organic matter occurs above 300°C which along with the accumulation of ash, base cations, and carbonates, increases the pH in higher temperatures (Yuan et al., 2011). Biochar yield is also decreased as the temperature rises (Demirbas, 2004b). Temperature rise increases the stability of the biochar, forming a poly-condensed aromatic structure of carbon (Baldock and Smernik, 2002) while reducing the functional groups by decarboxylation and dehydration, resulting in a reduction of ion exchange capacity (Demirbas, 2004b). Biochars at lower temperatures show an aliphatic structure, which is a typical characteristic of carbohydrates like cellulose and hemicellulose (Ghani et al., 2013; Qambrani et al., 2017)

4.2. Feedstock

Feedstock characteristics are one of the major determining factors of biochar quality. The selection of feedstocks depends upon the intended use of biochar and the method of preparation (Choudhary et al., 2019). Feedstock can broadly be classified based on moisture, source of biomass, and available condition of biomass, into wet & dry, plant, animal & industrial source, and terrestrial & aquatic source respectively (Yuan et al., 2019). Wet biomass requires extra energy and is less efficient compared to dry biomass since the water has to be evaporated initially during pyrolysis. Generally, feedstock having more than 30% moisture has been recommended to dry out before pyrolysis (Akhtar and Saidina Amin, 2012). As the moisture content increases, biochar yield decreases but the yield of bio-oil from wood increases (Demirbas, 2004a; Xiong et al., 2013). Similarly, the source of biomass also plays a huge role in changing the characteristics of biomass and ultimately biochar. The woody biomasses are high in calorific value and bulk density and have lower moisture and ash content. Whereas non-woody biomasses are low in calorific value and bulk density and high in moisture and ash content (Jafri et al., 2018).

The type of biomass also determines the pH, nutrient content, pore structure, ion exchange, and sorption rates of biochar. Behazin et al., (2016) found that Switchgrass and Miscanthus biochar had more Oxygen, Nitrogen, ash content, and volatile matter as compared to softwood chip biochar. Softwood chip biochar was found to be greater in fixed Carbon, surface area, and pore volume. Similarly, Ippolito et al., (2020) concluded that wood-based biochar had more surface area, pore volume, electrical conductivity, and C than other sources. Whereas the pH, ash content, cation exchange capacity, N, P, and K were the lowest. Manures biochar had the highest amount of ash content, N, S, P, Ca, Mg, Cu, B, Zn, Co, and Cl. The characteristics of agricultural wastes and grasses biochar were found to be in the middle ground between woody and manure biochar. CEC increases with the ash content of biomass since the alkali and alkali metals present might enhance the development of O-containing surface functional groups (Yang et al., 2015; Tag et al., 2016). Mineral content in biomass changes the outcome of biochar, resulting in less liquid oils and more char and gas, as inorganic materials can catalyze dehydration and charring (Tag et al., 2016). The presence of lignin and cellulose has been associated with higher production of biochar, so plant-based biochar is typically the one with more char production (Fields-Johnson, 2016; Al-Rumaihi et al., 2022).

4.3. Heating Rates

Heating rates of biomass determine the proportions of products obtained in the form of biochar, bio-oil, or gas. With a higher heating rate, the liquid, and gas yield increase due to fragmentation along with pyrolysis conversion, and the char yield is lowered (Uzun et al., 2006). The slow rate of heating results in secondary pyrolysis reactions and so it favors solid or char production (Ahmad et al., 2021). The effect of the heating rate is only influential on yield up to a certain temperature. Angin (2013) found that after 600°C only minor changes were found in yield due to the heating rate and the heating rate was more effective in lower temperatures. The polymer structure is only slightly changed at a lower heating rate and it requires more time to be properly pyrolyzed (Li et al., 2016). Unlike temperature, the heating rate does not change the composition of biochar but the crystallinity of biochar decreases as the temperature increases due to melting (Zeng et al., 2015).

5. Applications of Biochar

Although dynamic in nature and varied in use cases, the general and most applicable and distinct application of biochar can be seen in soil health and the environment. An overview of the applications of biochar within the broader fields is shown in Figure 8.

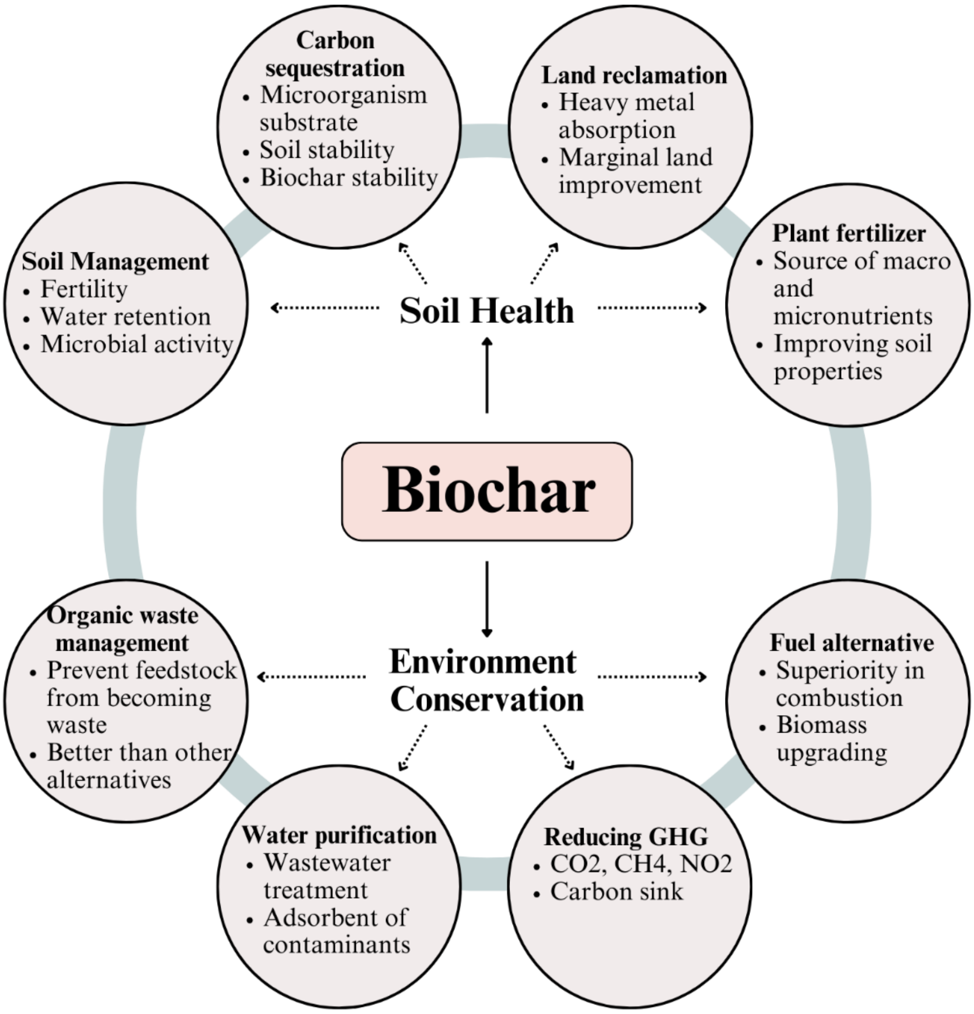

Fig. 8. Overview of the applications of biochar.

5.1. Soil Health

5.1.1. Soil management

Biochar application in soils significantly affects soil physical properties such as soil texture, porosity, surface area, pore size distribution, structure, bulk density, and particle size distribution (Chia et al., 2015; Qambrani et al., 2017). Biochar is highly used as an amendment for improving soil fertility. The multidimensional properties of biochar show it is a promising tool for environmental management, reduction in greenhouse gas (GHG) emissions mitigation, soil management, and soil fertility enhancement. Githinji (2014) reported the improvement of soil physical and hydraulic properties (porosity and Volumetric water context increases) by biochar application. The fertility of the soil is also improved for a long-lasting period because of biochar's higher nutrient retention and supplying capacity (Elshony et al., 2019; Glaser et al., 2002). The addition of biochar can increase soil fertility by leading to increased availability of extractable nutrients (N, P, K, Na, K, Ca, and Mg), and enhanced plant response to fertilizer promoting plant growth (Gaskin et al., 2010; Yuan et al., 2019), thus contributing to an improvement in the quality and quantity of crop production. Total nutrients from different feedstock sources get concentrated in biochar during conversion. Biochar application results in higher adsorption, and a decrease in the bioavailability of contaminants to microbial communities and plants in the soil. Khorram et al., (2016) have documented the biochar application effect resulting in degradation and low presence of pesticides, for soil amendment.

Biochar application effects are altered by various soil textural classes: leading to changes in water retention variables. Although Field capacity (FC) and wilting point (WP) increase for all textural classes, coarse-textured soil shows greater benefit (increased available water by 45%) after biochar application (Razzaghi et al., 2019). This could be attributed to high porosity, the presence of hydrophilic domains, and a large specific area of biochar (Weber and Quicker, 2018). The potentiality of biochar to improve soil fertility depends upon pyrolysis temperature and feedstock sources. Dai et al., (2013) found that biochar made from swine manures, leaves with high pH and macronutrients and fruit peels is a great way to increase soil pH and nutrient availability. Biochar soil management shows a high response on unfertile soil providing possibilities for sites that were not previously suitable for crop production (Lehmann and Rondon, 2006).

Biochar induces positive changes in microbial activity and community structure that result in soil improvement; enhancing carbon storage, soil fertility and quality, contaminants immobilization, and transformation (Zhu et al., 2017). This influence of biochar on microbial activity is because of, a) the large surface area and volume of pores that provide habitat for microorganisms (Quilliam et al., 2013), b) The availability of nutrients and ions adsorbed in biochar particles (Joseph et al., 2013), and c) the high sorption and degradation property of biochar for harmful soil contaminants and reducing the bioavailability and toxicity to microbes (Beesley et al., 2010; Qian and Chen, 2013). Acidic sandy soils treated with biochar provide a livable habitat for plants and soil-living animals (Molnár et al., 2016).

5.1.2. Carbon sequestration

Sequestration of Carbon (C) refers to the process of taking carbon out of the atmosphere, mainly in the form of CO_2 by plants via photosynthesis or other abiotic ways and storing it inside the soil, where it remains for a long period and is subject to the carbon cycle (Lal, 2008). Carbon levels in the atmosphere had mostly been in a balanced state until the last few decades which resulted in an increment of global temperature by 0.15°C every decade since 1975 (IPCC, 2007). The overall temperature of the world is expected to increase by 1.4–5.8 °C by the end of the 21st century (Cubasch et al., 2001). So, Carbon sequestration is important to prevent the net gain of CO_2 in the atmosphere, as warmer oceans take up less CO_2 (Mitchell et al., 2006).

In recent years, biochar has attracted attention as a sustainable solution for atmospheric carbon reduction and sequestering it in soil (Joseph et al., 2007). The stability of biochar in soil, along with its benefits to plants and microorganisms has a wide scope of use in agriculture, waste management, and as a tool for carbon control (Bolan et al., 2021). When applied to soil, it provides a substrate for microorganisms to grow, but the decomposition rate of biochar is very slow as compared to other organic materials (Joseph et al., 2007). Biochar only acts as a substrate and has very low usage by microorganisms as food. The increased mechanical strength than that of the biomass helps it tolerate the external effects and remain stable for longer (Downie et al., 2009). Kuzyakov et al., (2014) found that only 2.6% of the C input in the form of biochar resulted in microbial biomass after 1.7 years. It was also found that only 6% of biochar input in soil mineralized to CO_2 over 8.5 years and the mineralization rate decreased over time by 2 orders of magnitude. The Mean Residence Time of biochar applied in soil incubated at 20°C and 70% water holding capacity was calculated to be 400 years, which when extrapolated for the natural conditions resulted in a residence time of 4000 years. It was also concluded that the decomposition rate primarily depends upon the biochar characteristics and not the soil type, but the rate can be influenced by factors like freezing/thawing, drying/wetting, microbial activity, and soil mixing by animals or other natural causes. The residence time of this scale is much greater than the source organic material and therefore it results in the net withdrawal of atmospheric CO_2 over a period of time (Lehmann, 2007). The carbon sequestration potential of biochar is estimated to be 0.7-1.8 Gt CO_2-C equivalent per year, which equates to 3.33% of the total CO_2 emission in 2022 (Smith, 2016; Tollefson, 2022). If utilized properly, biochar can be one of the most effective ways towards carbon negative and reaching the climate goals.

Another product similar to biochar, hydrochar, is produced through the process of hydrothermal carbonization. There are many uses of hydrochar like soil amendment, wastewater treatment, solid fuel, adsorbent for pollutants and chemicals, etc. (Lucian and Fiori, 2017), but it hasn't been successfully used for carbon sequestration yet because of its instability in soil. Malghani et al., (2013) showed that the half-life of hydrochar in the soil was just 100 days which was very low as compared to the half-life of 2000 days of biochar.

5.1.3. Land reclamation

Land reclamation refers to the act of restoring fertile lands to their original form of productivity, and natural state, and improving the condition of otherwise hostile, barren, and infertile land for some intended functionality (Ukhurebor et al., 2022). Every year, with the increasing population, activities like fossil fuel extraction, mineral extraction, deforestation, and unmanaged use of land for housing and industries have been increasing especially in developing countries, which harm the environment. In the long run, these activities result in a heavy loss of functional land. Currently, land degradation affects almost 2 billion hectares of land worldwide with 12 million hectares degraded every year, and fertile soils nearly 24 billion tons are lost due to erosion every year (FAO, 2023). Soil erosion has been associated with cropping area increment where the erosion in conventional agriculture is about 380 times than the natural soil formation rate (Bhadwal et al., 2019). Oil, gas extraction, and mining operations are other activities that ruin the quality and state of land (Favas et al., 2018; Bhadwal et al., 2019).

Biochar has proven to be one of the potential tools for reclamation of the degraded land (Ippolito et al., 2018). The long-lasting nature of biochar and its ability to adsorb heavy metals and toxic substances make it such a great option. Heavy metals such as Aluminum (Al) and Manganese (Mn) in acid soils and Arsenic (As), Cadmium (Cd), Copper (Cu), Nickel (Ni), and Lead (Pb) in heavy-metal contaminated water and soil can be adsorbed by biochar (Uchimiya et al., 2010). This is mainly due to the surface of biochar with an abundance of chemically active groups (e.g., OH, COOH, and ketones). Guo et al., (2020) conclude biochar’s performance in alleviating drought and salinity stress, changes the heavy metals and organic pollutants from soil to plants. Biochar application to forests improves and enhances soil physical and chemical properties and also increases microbial biomass (Li et al., 2018). The efficiency for removal of heavy metal ions (Cu^{2+}, Pb^{2+}, Ni^{2+}, Zn^{2+}, Sb^{2+}, Cd^{2+}) from aqueous solution is influenced by biochar sources, e.g., sewage sludge, animal waste, agricultural by-products (Lima et al., 2010). Animal manure-derived biochar is found highly effective for precipitating Hg^{2+} while hardwood, straw, and dairy manure derived biochar reduces about 35-92 % of Cd^{2+}, Zn^{2+}, Pb^{2+}, and Cu^{2+} (Lin et al., 2017).

Similarly, the pH amendment capability, porous nature, CEC, and C increment in soil by biochar make it a suitable technique for marginal land improvement. Hailegnaw et al., (2019) found that the application of biochar in soil with less pH, CEC, and Ca^{++} than the biochar resulted in their increment. As explained in the above segments, the stability of biochar ensures a steady supply of substrate for nutrients, water retention, and growth and expansion sites for microorganisms and plant roots for a long time. The low cost and ease of production combined with various benefits make biochar an excellent choice for land improvement and climate-smart agriculture (Cowie et al., 2017).

5.1.4. Biochar as plant fertilizers

The characteristics and properties of biochar depend on various factors like the feedstock used, the temperature during production, and the methods of preparation as explained in section 2 and 4. As such, it is not possible to generalize the effects of biochar into categories, and the effects fall under a spectrum ranging from inhibiting effects on plants to promoting plant development. Researchers have found that the beneficial effect of biochar is obtained more when used with other organic amendments like compost, Farm yard manure, leaf litter, etc. (El-Sherpiny et al., 2023; Schulz et al., 2013). Still, it depends heavily on the nature of the amendments used. Bonanomi et al., (2017) have shown that the biochar application generally does not show much variation in terms of plant responses with a majority of biochar promoting plant growth, but the addition of organic supplements along with biochar resulted in the occurrence of more inhibitory effects than positive. It has been found that the combination of lignin-rich biochar and organic amendments rich in nitrogen (N) content is the most beneficial, while N-rich biochar mixed with high C/N organic amendment is not beneficial and inhibits plant growth (Bonanomi et al., 2017). The growth inhibitory effect is caused by the initial uptake of soil N by the microorganisms responsible for the breakdown of organic amendments, without subsequent replenishment (Hodge et al., 2000). The higher N content in biochar feedstock does not inherently make it a good choice for biochar production since the available N is probably converted into pyridine-like compounds, which become inaccessible to plants (Chan and Xu, 2009). Nevertheless, several beneficial effects of N from the application of biochar have been observed (Azeem et al., 2019).

Similarly, the effect of biochar application on the P and K availability to plants is also variable and depends on feedstock, production temperature, and preparation methods, and these factors must be considered before the application of biochar. P when applied to the soil goes through sorption, precipitation by reaction with other elements or compounds, and immobilization by the microorganisms, and only about 20% of the P is available for plant uptake (Zhu et al., 2018). The application of biochar helps reduce the precipitation of P by cations like Al3+, Fe2+, Fe3+, and Ca2+, by adsorbing cations to its negatively charged surface area (Xu et al., 2014). Similarly, biochar also releases dissolved organic matter in the form of organic ligands (molecules with functional groups that bind to central metal atoms), which form complexes with aluminum and iron oxides. The reduced availability of the oxides prevents the adsorption of P and increases its availability for plants (Liu et al., 2018). Moreover, biochar also increases the P availability in the soil by acting as a bio-fertilizer and gradually releasing P after a certain period (Silva Mendes et al., 2015). Similar to P, the application of biochar has been found to increase the potassium (K) availability in soil since biochar itself contains a high amount of K, typically ranging from 0.70 to 116 g kg−1 (Ippolito et al., 2015). It has been reported that biochar prepared under higher temperatures over 700° C has a higher K concentration because of K's higher volatilization temperature (DeLuca et al., 2015). The concentration of K tends to increase with increasing pyrolysis temperature and is changed from its complex form in the feedstock to water-soluble forms like potassium nitrate, potassium chloride, and potassium sulfate, which are readily taken up by the plants (Zheng et al., 2013; Tan et al., 2017). Many positive effects in plants have been attributed to the increase in soil potassium resulting from the application of biochar such as an increase in growth and yield in cotton (Wu et al., 2019), an increase in the dry weight of zucchini (Tolba et al., 2021), improvement in cotton fiber quality (Tian et al., 2018), and increase in dairy pasture yield (van Zwieten et al., 2019).

Biochar application also benefits plant growth by improving the soil chemistry, stabilizing pH, EC, and other properties, water holding capacity, and absorbing the harmful compounds to reclaim barren and wastelands (Khalil et al., 2023). It also reduces the bulk density, which assists in plant root system to develop (Zhang et al., 2021b). However, there is need to consider the source materials (feedstock) of biochar, whether they contain heavy metals and toxic volatile organic compounds such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCBs), and polychlorinated dibenzodioxins (PCDDs), that will make its way into the soil through the application of contaminated biochar, which may inhibit the growth of plant and soil microorganisms (Ghodszad et al., 2021).

5.2. Environment Conservation

5.2.1. Organic Waste Management

With the start of the green revolution, there has been a substantial increment in the overall production and productivity of crops. Almost triple production has been achieved because of it with only a 30% increment in agricultural land (Pingali, 2012). The increased production also increased agricultural wastes, particularly crop stubbles, and stalks. The problem was increased due to the shortening of the crop cycle and higher biomass of the hybrid crops. Management of residues by haphazard burning has become one of the chief causes of air pollution and ecological disturbance (John and Babu, 2021). The population is expected to reach 9.7 billion by 2050 and so comes the challenge of food security and waste management associated with it (UN, 2023). Wastes generated in food production also include livestock wastes and industrial wastes like manure, dung, carcass, bio-gas slurry, sugarcane bagasse from sugar industries, etc., which are equally harmful if not managed properly (Mengqi et al., 2021). Over 61% of total solid waste produced by humans has an organic origin and food waste accounted for over 50% of the CO_2 emissions from solid waste treatment and disposal in 2016 (The World Bank, 2018). One of the ways of reducing waste and the problem it creates is by converting the wasted biomass into biochar. The otherwise wasted energy can be harvested from biomass, creating an alternative source of clean energy and income (Lee et al., 2018; Owsianiak et al., 2021). The heating value of crop residues is 50% of coal and 33% of diesel, which is a promising sign for utilizing agricultural wastes for biochar (Lal, 2005).

Utilizing waste biomass as a feedstock for biochar preparation has a myriad of benefits. Biochar preparation can replace composting and landfilling of biomass, preventing the release of CH_4 and N_2O, which are potent greenhouse gases (Bolan et al., 2013). The transportation cost, which ranges from $20-$30 per ton (The World Bank, 2018), and emissions during transportation are also minimized. Biochar preparation is also a faster way to manage waste and improve crop productivity than either landfill or composting (Ayilara et al., 2020). The longer stability and porous structure of biochar also mean that it is a better alternative to composting in loosening the soil (decreasing bulk density), and creating a stable soil structure as well as carbon substrate, all while preserving its nutrient content and increasing the nutrient and water retention capacity of the soil (Burrell et al., 2016). Agegnehu et al., (2016) found that biochar (10 t/ha) in combination with usual chemical fertilizers had the highest grain yield and total biomass compared to the use of only regular fertilizer, compost (25 t/ha), and regular fertilizer, and a combination of regular fertilizer, biochar (2.5 t/ha) and compost (25t/ha). Biochar from residual straw increased the photosynthesis rate, chlorophyll content, soil nitrogen content, and amino acids in maize kernel up to a level, beyond which biochar started showing negative effects on these parameters (Khan et al., 2022). Unlike other products of organic materials, biochar is easy to store, use, and transport, and is free from any pathogen or insect pest (Ayilara et al., 2020). However, the inorganic materials present in the feedstock are concentrated in the final product, so the presence of heavy metals in the biomass and the formation of PAHs by pyrolysis need to be considered before creating and using biochar (Ippolito et al., 2012).

5.2.2. Water Purification

Under the rising world of technology, biochar is a promising tool for the sustainable wastewater management of the growing population. Presently biochar has been widely studied to deal with water pollutants and wastewater. Biochar enriched with nutrients can act as a filter medium for wastewater treatment to reduce pathogen loads which directly leads to lower health risks to farmers and consumers (Werner et al., 2018). Biochar is an efficient wastewater treatment system capable of utilizing locally available resources and low cost of production. Kaetzl et al., (2020) documented the effectiveness of Miscanthus–biochar over sand filters in the removal of Chemical Oxygen Demand (COD) and *E. coli* from municipal wastewater. This outcome is the result of Miscanthus biochar with a low H/C-(0.19) and O/C- (0.08) ratio and higher surface area than that of sand. The high porosity and adsorption property of biochar allows pollutants from wastewater to accumulate on its surface resulting in clean effluents and nutrient-rich biochar (Foereid, 2015). Manyuchi et al., (2018) reported wastewater passed through the biochar bio-filter resulted in the reduction of COD, Total Suspended Solids (TSS), Total Kjeldahl Nitrogen, and total Phosphate by 90%, 64%, and 78%, respectively. Kaetzl et al., (2018) also found a reduction of COD (up to 90%), Total Organic Carbon (up to 80%), and FIP (Facial Indicator bacteria) (up to 1.7 $\log_{10}$-units) by anaerobic filters. These results show the superiority and effectiveness of biochar for wastewater treatments.

Biochar is an effective adsorbent for various organic and inorganic contaminants, having the potential to be used to sustainably remove them from water. The richness of stable carbon in biochar provides a higher potential for handling wastewater contaminants. Mohan et al., (2014) reported the biochar application for organic (dyes, phenolics, pesticides, polynuclear aromatics, and antibiotics) and inorganic (cations and anions) pollutants remediation of wastewater. This is due to the high surface area and pore volume, abundant surface functional group, and functionality (high adsorption capacity) of biochar (Law et al., 2022). Biochar produced under pyrolysis at high temperatures is suitable for organic contaminants sorption whereas low-temperature treated biochar is suitable for inorganic contaminants (Enaime et al., 2020). The removal efficiency of biochar for pollutants from wastewater depends upon its type and physiochemical properties of pollutants. Biochar derived from sawdust removed 20.3 mg/L (Reguyal et al., 2016), wood removed 20-30% (Shimabuku et al., 2016), and organic farm residue removed <6% (Lin et al., 2017) of sulfamethoxazole while rice husk derived biochar produced at 500°C showed removal efficiency of 90% for tetracycline 5 mg/L (Wang and Wang, 2019).

5.2.3. Greenhouse gas emissions (GHG) mitigation

CO_2, Methane (CH_4), and N_2O are the major contributors to GHG in the atmosphere and global warming (Lehmann and Joseph, 2009; Calzadilla et al., 2013). Biochar application is attaining a major interest in the mitigation of global warming and improvement in crop productivity. Biochar, a way for sequestering carbon in soil is a significant tool in reducing the greenhouse gases in the atmosphere (Joseph et al., 2007). Biochar application combined with controlled irrigation in paddy fields has shown improvement in soil health, mitigation of greenhouse gas emissions, and mediation for soil microbial community structure (Jiang et al., 2021). Agronomic practices such as drainage of wetlands, plowing, land use change, paddy fields, fertilizers, livestock, and wetlands are the major sources of GHG (CH_4 and N_2O) (Silva et al., 2011; Gogoi and Baruah, 2012; Yao et al., 2012). F. Wu et al., (2013) found a dramatic reduction of N_2O emission but no difference in CO_2 or CH_4 emissions when biochar was applied at rates of 0.6% and 1.68% in Chernozemic soil. Biochar amendment has resulted in a decrease of N_2O by 50% in soybeans and 80% in grass fields grown in barren Oxisol in the Colombian savanna (Zhang et al., 2019a). These N_2O emission rates are highly affected by feedstocks, biomass conversion parameters, and C/N ratios. The emission of N_2O is also affected by specific temperature and moisture conditions (Fidel et al., 2019). F. Wu et al., (2013) conclude the reduction of N_2O and increase of CO_2 emissions from soils after biochar application. A large scale of lignocellulose biomass-derived biochar is used nowadays which is a key to mitigating climate change globally through biochar application (Case et al., 2014; Sri Shalini S et al., 2021). Biochar is a possible sustainable material for reducing the concentration of atmospheric CO_2 where its sustainable application can decrease 12% of current anthropogenic CO_2-C equivalent emissions (Woolf et al., 2010).

Carbon sequestration from biochar is an important strategy to reduce GHG emissions. Biochar improves water and soil quality due to its recalcitrant nature to draw carbon from the atmosphere and provides a carbon sink to the terrestrial ecosystem (Lehmann and Joseph, 2009). Algal-derived biochar can replace chemical fertilizer to an extent as microalgae are rich in nutrients and have a high potential for CO_2 capturing which helps GHG emission mitigation (Mona et al., 2021). GHG emissions from agricultural land is one of the major contributors to global warming. Thus, the application of biochar 30 t ha^{-1} as a way of mitigating GHG emissions has been reported to be effective along with achieving optimum crop yield (Shakoor et al., 2021). Biochar amendment at 20 t ha^{-1} without N fertilization resulted in a 15.8 % increase in maize yield and a reduction of N_2O emission by 10.7 % as compared to no biochar amendment soil with N fertilizer in calcareous and infertile dryland cropland poor in soil organic carbon (Zhang et al., 2012). Case et al., (2014) conclude the potentiality of hardwood biochar to improve the GHG balance of bioenergy crops by reducing the net soil CO_2 equivalent emissions.

5.2.4. Biochar as a fuel alternative

The world's energy demand is skyrocketing with the growing population. Biochar fuel is an alternative solid fuel generated from renewable energy sources for the sustainable fulfillment of global energy needs. The *Leucanea leucocephala* biochar showed a rise in concentrations of fixed carbon (151.82%), ash (80.56%), Carbon (40.06%), nitrogen (144.63%), and higher heating value (38.69%) whereas a fall in the volatile matter (41.49%), moisture (88.16%), hydrogen (75.16%), Sulphur (7%), and oxygen (50.44%) (Anupam et al., 2016). The reduction in oxygen, volatile matter, and increment in Carbon and fixed carbon highlights the potential of biochar being a superior fuel source. Rice husk-prepared biochar at a temperature of 432°C, heating rate of 4°C/min, and time of 40 min resulted in a higher heating value (25.08 MJ/kg), yield (54.65%), energy density (1.46) and energy yield (79.66%) which shows the superior quality and higher yield of solid biofuel (Yadav et al., 2019). Sinha et al., (2013) found that linseeds (*Linum usitatissimum L.)* pyrolyzed at a temperature range of 350-575°C and heating rate of 20°C/min produced pyrolysis oil whose physical properties are close to the petroleum fractions.

The physicochemical properties such as; large surface area, multi-scale porous structure, and tailoring functional groups of biochar make it a potential catalyst for many applications of biochar (Liu et al., 2015; Chi et al., 2021). Biochar as a catalyst supports biomass upgrading, biodiesel production, biomass pyrolysis, gasification, and bio-oil upgrading (Cao et al., 2017; Jiang et al., 2021). A heterogeneous catalyst; pyrolyzed rice husk with concentrated sulfuric acid has been used for biodiesel production from waste cooking oil with a high free fatty acid. M. Li et al., (2014) documented 98.17% free fatty acid conversion to biodiesel after 3h and 87.5% Fatty Acid Methyl Ester conversion after 15h. The surface area and acid density of biochar also significantly affect biodiesel production. Biochar catalyst; palm kernel shell after gasification resulted in producing a 99% yield of biodiesel from the sunflower oil (Bazargan et al., 2015). Biochar addition during the microwave torrefaction process with a temperature of 250°C and residence time of 20 min gave potentiality for camelina straw and switch grass for making biofuel pallets (Agu et al., 2022).

6. Constraints

Although biochar has been regarded as a highly beneficial product with its varied usage cases and ease of availability, it still has some potential drawbacks decreasing its preference and use. Agriculture is one of the fields that directly benefit from its application as it helps manage land for better soil health and crop productivity. But it has to be used carefully since it affects various soil physical and chemical properties and the application effect can create unwanted results. The sorption capacity of biochar being high brings about the inactivation of the chemicals, rendering them useless while adsorbed. As a result, a greater amount is needed than normal for the chemicals to be effective in biochar-amended soil. In an experiment conducted by Yu et al., (2009), it was found that the bio-availability of two insecticides (Chlorpyrifos and Carbofuran) in spring onion (*Allium cepa*) was reduced after the soil application of 1% woodchip biochar over a period of 35 days. Even though the loss of insecticides from soil was reduced, which may prevent pollution in other areas, the insecticides remained sequestered in the soil with biochar particles, potentially resulting in long-term soil pollution. Sorption and immobilization of heavy metals and toxic compounds create a precarious situation as the sorbed chemicals can make their way back into the environment. In such cases, the soil or water where biochar is used as a sorbent will face the consequences of increased concentrations of toxic substances (Kuppusamy et al., 2016).

The pH of the soil is another aspect where care must be taken to avoid undesirable results. The pH of the soil is generally increased following biochar application, affecting the nutrients availability and microorganism and plant growth, which typically is best in the pH range of 6.1-7.8 (Msimbira and Smith, 2020). However, the change also depends on the soil type and the environmental conditions with varying outcomes. M. Zhang et al., (2019) reported that biochar application in soil simulated with 25 mm rainfall resulted in a pH increase of 0.5-1 in yellow-brown soil and fluvo-aquic soil, but no changes were observed in lou soil which is mostly found in shoulder and summit positions in the landscape. Similarly, the decline in N levels and usage by plants have been reported in some cases due to biochar application, where there was a need for additional N for maximum crop production (Nelson et al., 2011) and report of the indifference of biochar toward N use efficiency by Güereña et al. (Güereña et al., 2013).

The presence and release of PAHs is one of the major issues surrounding biochar use and production. PAHs have harmful characteristics to human and plant health and show mutagenic, teratogenic, and carcinogenic properties in the long run (HHS, 1995). Naphthalene is the chief compound released during pyrolysis and by the biochar in soil (Buss et al., 2022). Although being the least toxic among all PAHs, and having a short half-life of just 2 days, it is still considered a hazard and can cause minor altercations in the health of humans, soil microbes, and plants (Delistraty, 1997). Certain levels of PAHs were found in the crops grown in biochar-amended soil and the total mean incremental lifetime cancer risk for adults was calculated to span from 2.0×10^{-6} to 1.9×10^{-5} when in contact with or consuming crops grown on such amended soils, but the overall cancer risks due to the exposure were low (Wang et al., 2019). One hopeful prospect for the use of biochar despite PAHs release is that Naphthalene is the most volatile PAH, with a volatilization rate of 30% in soil (Park et al., 1990).

Moreover, Biochar has been found to change the surface albedo of the amended soil, but the quantification is yet to be done thoroughly. Under general conditions, the albedo of soil decreases with the darkening of its color, resulting in the absorption of energy from the UV light. This has been reported to decrease the climate mitigation benefit of biochar systems by 13-22% (Meyer et al., 2012).

7. Trends, Economic analysis, and adoption of biochar

Biochar with its multifaceted use has been experiencing a rise in global attention. The Biochar industry has seen huge success in recent years with China leading the global production of biochar by producing 300,000-500,000 Mg yr^{-1}, followed by the USA with ~50,000 Mg yr^{-1}, Europe with 20,000 Mg yr^{-1} and Australia with 5,000 Mg yr^{-1} (Garcia et al., 2022). The production has been increasing throughout the years; EBI, (2023) reported the installation and commission of 28 new biochar production plants in 2022 alone, resulting in a cumulative number of plants to be 130 across Europe. The use and production of biochar are increasing due to the need for a 'Circular Bioeconomy' for a sustainable future (Nematian et al., 2021), which refers to the use of renewable resources, reducing pollution and waste, and replacing fossil-based resources (CIFOR, 2021). Biochar proves to be an excellent resource, reinforcing the circular bioeconomy due to its many applications as described in section 5. But a proper understanding of the advantages and associated economics of biochar, and knowledge about biochar itself is needed for its adoption by the farmers. An analysis done by Latawiec et al., (2017) in Poland found that 27% of the interviewed people knew about biochar and 20 % were willing to adopt it while 43% were not willing and 27% of people couldn't say for sure. But those who had heard of biochar before had an increased percentage of people willing to adopt it than those who hadn't heard of it before, which concluded the direct relationship between willingness to adopt and prior knowledge. Two of their major concerns revolved around the cost and the effectiveness of biochar, so they have to be addressed with proper research and dissemination of the findings to increase the adoptability of biochar.

The average cost of biochar has been estimated to range from \$450 to \$1850 Mg^{-1} (USD) (Nematian et al., 2021), which can be a significant amount, deterring its adoption by lower-scale farmers. Further discouraging the use of biochar in agricultural lands is its ability to substitute low-grade coals, earning farmers approximately \$150 to \$300 Mg^{-1} quickly, in contrast to the long-term soil benefits which can often go unattended by the farmers (Maroušek et al., 2019). Taking carbon offset into account, the cost of biochar can be reduced to \$193- \$234 (USD) Mg^{-1} (Thengane et al., 2021), which will be more manageable for a wide range of farmers, and can even make biochar use a practical and viable practice. However, there should be proper promotion and dissemination of this information for it to cause much change in the adoption practices among farmers (Latawiec et al., 2017).

8. Future Prospects of Research

Biochar has been deemed as a solution for C balance and as a way of mitigating climate change. However, there have not been many findings regarding the long-term behavior and characteristics of biochar in soil. The durability of biochar is very high and because of the longer time required, calculation of the deterioration rate of biochar in soil and soil types has been difficult and is yet to be calculated thoroughly. Long-term emission rates of gases like CH_4, N_2O, etc. from biochar-amended soil are seldom found. In some instances, short-term data have been used to estimate for a longer period but that may not hold in natural environmental conditions. The mobility of biochar in soil and its release in water has also not been studied much. There have been numerous characterizations of biochar prepared from different feedstock but their effect on soil and microorganisms is a field that is yet to be explored. A study of different production conditions and feedstock combinations would be of high importance to correlate it with the fate of biochar in soil, soil properties, and effects in plants, ultimately determining the attainability of the intended use of biochar. There is scope in studying the economy of using different feedstocks concerning the products formed and their quality as well. The ecotoxicological impacts and effects on human health should be a priority as it is of paramount importance and not much work has been done regarding them. Working on the production method, emission and application will help standardize, monitor, and mitigate the harmful effects of biochar and assist in proper policy-making.

9. Conclusion

Biochar has proved to be an excellent resource and has received increased attention since the discovery of its association with the fertility of 'Terra-Preta' soil. The various methods of production of biochar as discussed include Pyrolysis, Hydrothermal carbonization, Torrefaction, and Gasification, which produce different levels of output of biochar, syngas, and bio-oil. Appropriate production methods should be used according to the intended use of biochar and available resources and materials. The physical and chemical properties mentioned highlight the areas where the application of biochar can affect soils and the environment. Other than soil amelioration and land reclamation, biochar has also proved to be useful in a wide range of practices like organic waste management, water purification, Greenhouse gas emission mitigation, and carbon sequestration, and acts as a fuel alternative, which merits increased popularity that it has received. Even though the knowledge about biochar properties and usage has been increasing, further advancements can still be done in some areas like the effects of different feedstock in biochar properties, standardization of biochar usage, long-term biochar and soil relationship, etc. Biochar as a climate change mitigating tool and its part in climate resilient agriculture has still not received as much attention as it deserves, which could be remedied by proper policy-making, dissemination of its importance to the public, and development of easily accessible biochar production methods. Overall, the increment in biochar interest is a positive step towards climate change mitigation and developing a climate-resilient agricultural food system globally.

Declarations

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

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