Sustainable biochar: A facile strategy for soil and environmental restoration, energygeneration, mitigation of global climate change and circular bioeconomy

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Abstract

The increasing agro-demands with the burgeoning population lead to the accumulation of lignocellulosic residues. The practice of burning agri-residues has consequences viz. release of soot and smoke, nutrient depletion, loss of soil microbial diversity, air pollution and hazardous effects on human health. The utilization of agricultural waste as biomass to synthesize biochar and biofuels, is the pertinent approach for attaining sustainable development goals. Biochar contributes in the improvement of soil properties, carbon sequestration, reducing greenhouse gases (GHG) emission, removal of organic and heavy metal pollutants, production of biofuels, synthesis of useful chemicals and building cementitious materials. The biochar characteristics including surface area, porosity and functional groups vary with the type of biomass consumed in pyrolysis and the control of parameters during the process. The major adsorption mechanisms of biochar involve physical-adsorption, ion-exchange interactions, electrostatic attraction, surface complexation and precipitation. The recent trend of engineered biochar can enhance its surface properties, pH buffering capacity and presence of desired functional groups. This review focuses on the contribution of biochar in attaining sustainable development goals. Hence, it provides a thorough understanding of biochar's importance in enhancing soil productivity, bioremediation of environmental pollutants, carbon negative concretes, mitigation of climate change and generation of bioenergy that amplifies circular bioeconomy, and concomitantly facilitates the fulfilment of the United Nation Sustainable Development Goals. The application of biochar as seen is primarily targeting four important SDGs including clean water and sanitation (SGD6), affordable and clean energy (SDG7), responsible consumption and production (SDG12) and climate action (SDG13).

Keywords: *Biochar; Agro-wastes; Soil and environment management; Climate change mitigation; Bioenergy; Sustainable development goals*

1. Introduction

Agro-ecosystems can play vital roles, in one way, by ensuring the food security for billions of people and, on the other hand, being instrumental in efficient utilization of available resources, mitigating GHGs emissions and climate change (Bhattacharyya et al., 2020). In this context, overall agro-ecological functioning needs to ensure more sustainable ways of agriculture practices such as reduced usage of chemical fertilizers for enhancing food production without compromising the productivity and health of the soil, sustained increase in crop yield, boosting sequestration of carbon and depleting GHGs emanation (Khan et al., 2021; Bhattacharyya et al., 2021). The stress of feeding growing population, limited arable land, inefficient consumption of essential resources and amassing agro-residues has necessitated the need of a sustainable solution for the management of strained agricultural systems (Dhamodharan et al., 2020). The conventional way of handling the huge biomass generated from the agriculture sector is the burning of residues, which leads to the emission of nitrogen oxides (NO_x), sulfur (SO_x), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), particulate matter (PM) and carbon monoxide (CO). The prolonged exposure of these compounds has serious implications on environment and human life (Apicella et al., 2021; Xie et al., 2015).

Biochar, a carbonaceous solid product of biomass pyrolysis, has been emerged as an efficient, environment friendly and cost-effective approach for achieving sustainable development goals. According to the IPCC report 2018, biochar is considered as the promising negative emission technology (NET). Biochar recovery from agricultural biomass has numerous advantages over direct combustion, including long-term carbon storage, biomass decay prevention, fossil energy offsets, and reduced emissions of harmful green house gases while simultaneously improving physicochemical and biological properties, soil quality, crop yields, and bioenergy generation

(Woolf et al., 2010; Luo et al., 2021; He et al., 2021). Biochar is derived from a various sources such as agricultural crops and remnants, agroforestry, industrial and municipal solid waste, by pyrolysis (fast/slow) at 300-800°C in anoxic conditions (Yaashikaa et al., 2020), with generation of bio-oil and syngas in parallel. From the perspective of sustainable agriculture system, agro-resources such as rice husk, wheat straw, coffee husk, sugarcane bagasse etc., are considered as the most popular sources for the synthesis of biochar (Chowdhary et al., 2021; Yang et al., 2019).

The application of biochar is purpose-oriented and context-specific, and is largely governed by biochar's physicochemical characteristics, that rely upon thefeedstock type and conditions of pyrolysis. Biochar possesses useful properties like high surface area, large pore size, stable structure and presence of functional groups, which makes it suitable for wide range of applications (Weber and Quicker, 2018). Biochar has been commonly used for soil amendment and enhancing soil properties for better nutrient availability, increasing soil fertility, buffering soil pH and enhancing carbon sequestration. In recent studies, biochar is also used as animal feedstock for efficient nutrient uptake in livestock farming for improving animal health and enhancing the productivity (Schmidt et al., 2019). Recent trend of developing engineered biochar is gaining significant attention and numerous reports are available for efficient removal and mitigation of heavy metals, toxic dyes, contaminants of emerging concerns from municipal wastewater and industrial effluents (Luo et al. 2021; IBI, 2013; IBI, 2014; Deng et al., 2017; Zhang et al., 2018; Yaashikaa et al., 2019). Production of biofuels (bio-oil and syngas), along with biochar during pyrolysis, has been linked with the sustainable consumption of biomass resources. Recent reports have suggested the application of biochar for assisting and enhancing the processes involved in the generation of bioenergy and construction materials, improving the overall environmental benefits and helping in agro-waste recycling (Arif et al., 2020).

The United Nations has specified 17 ambitious SDGs to be attainable by the year 2030 (Gaşior and Wilhelm, 2017). Strategies focusing on the implementation and implications of sustainable development have suggested the necessity of efficient consumption of natural resources, inexpensive and clean energy, potable water and sanitation, and mitigation of climate change (UN 2016; Smith et al., 2019). With regard to achieving SDGs, biochar has become a promising and attractive tool because of its cost-effectiveness, and ability of enhancing food production, efficiently adsorbing contaminants present in wastewater, and transforming bio-waste to bioenergy (Wang et al., 2021). Biochar can directly contribute in achieving SDGs such as clean water and sanitation (SDG6), affordable and clean energy (SDG7), responsible consumption and production (SDG12) and climate change (SDG13). The article aims to produce a detailed insight and know-how on the importance of biochar-based approaches for the enrichment of agricultural soil, degradation and removal of pollutants, generation of bioenergy and mitigation of climate change. Recent reports available on the fabrication of biochar and its composites, along with their applications, are presented. The role of biochar in boosting circular bio-economy and achieving SDGs has also been discussed.

2. Engineered biochar and their properties

Engineered biochar or biochar composites are the form of biochar modified with the materials such as metals, nanomaterials, microorganisms, hydroxides etc., to enhance the characteristics of raw biochar. They are classified as mineral biochar, metal biochar, microorganism biochar, carbonaceous nano-composites and layered double hydroxide (LDH) biochar composites (Wang et al., 2021). Mineral biochar were prepared by the co-pyrolysis, co-precipitation and immobilization of minerals such as Montmorillonite, Attapulgite, Struvite, etc. These mineral based biochar can be used to improve the fertility of the soil and help in gradient release of fertilizer (Chen et al., 2017; Wang et al., 2021; Hu et al., 2019). Metal doped or fabricated biochar's such as iron-oxide biochar, nano zero valent iron (nZVI) biochar and iron-sulphide biochar are among the popular metal biochar composites, whereas MgO, MnO_x, MoS_2-coated biochar composites are also reported. Usually, transition metals are known to facilitate the catalytic action of biochar (Zhang et al., 2020; Liu et al., 2021; Wang et al., 2021). Metal biochar is known to have improved adsorption capacity on the removal of pollutant and heavy metals (Lyu et al., 2020; Wang et al., 2021; Shen et al., 2019; Hamid et al., 2020). Biochar equipped with microbes such as *Bacillus siamensis* and *Mycobacterium gilvum* are called as microorganism biochar, and they can be used to achieve increased degradation of stubborn contaminants, decomposition of soil PAHs, soil metal immobilization and nitrogen fixation (Feng et al., 2020; Kumar et al., 2021; Xiong et al., 2017; Tu et al., 2020; Wei et al., 2020). The presence of large amount of π electrons in the modified nano composites made them suitable candidates for adsorption dependent applications. Therefore, multiwalled carbon nanotubes (MWCNTs) and graphene-based biochar are widely utilized for the adsorption of organic pollutants such as sulfamethazine, phthalic esters and methylene blue (Wang et al., 2021; Inyang et al., 2014). LDH-biochar composites consist of anionic clay minerals and biochar, where minerals provide the metal hydroxide layers (positively charged) and interlayer space consists of anions, required for the purpose of neutralization. Mg-Fe, Zn-Al, Ca-Al, Ni-Fe and Mg-Alare commonly used for LDH-biochar composites, leading to improved anion-exchange capacity and supporting co-precipitation andsurface complexation by providing hydroxyl groups (Ma et al., 2016; Bolbol et al., 2019; Gaoet al., 2019; Wan et al., 2017).

The feedstock type (nature of biomass) and operating temperature at which biochar is synthesized determines the characteristics namely, surface area and porosity of biochar (Suárez-Hernández et al., 2017; Weber and Quicker, 2018). For synthesis from agricultural waste products, with increasing temperature, surface area and overall pore sizeof biochar gets enlarged, while decreased in particle size (Singh et al., 2019). The pyrolysis temperature is critical for pore formation; usually 600-700°C is the critical temperature range for micropore formation (Tomczyk et al., 2020). Also, biochar's cation exchange capacity (CEC) has been found to increase with an increasing surface area. The surface area and pore size of biochar are considered as crucial parameters for contaminant remediation (Askeland et al., 2019).

Various methods and instrumental studies have been employed for the in-detail characterization of biochar. The ultimate composition of biochar,such as carbon (C), nitrogen (N), hydrogen (H), sulphur (S) and oxygen (O) can be measured using elemental analysis. Biochar's surface area and pore size distribution which reflect the morphological and physical properties has been widely determined by the physio-sorption method. The surface characteristics and existence of various functional groups are usually studied by performing Spectroscopy and Scanning Electron Microscope (SEM) and Fourier Transform Infrared (FTIR) (Jechan et al., 2017; Rathnayake et al., 2021, Ahmad et al., 2021a; Ahmad et al., 2021b). Atomic Absorption Spectrometer (AAS) and/or Inductively Coupled Plasma Mass Spectrometer (ICP-MS) were used to detect traces of heavy metals in biochar (Jechan et al., 2017).

Organic material emanating from agriculture and agro-forestry and being suitable as feedstock for subsequent thermal processing typically includes bagasse, straw, nutshells, husks, bark, sawdust etc. Biomass is mainly composed of cellulose, hemicelluloses and lignin. Apart from these, it has been found that starches, proteins, minerals, oils,nucleic acids, and resins are also present (Li et al., 2014). In most plant derived biomass, cellulose dominates whereas lignin dominates in woody biomass. Cellulose in biomass varies in the order of 40-60 wt.%. Hemicelluloses remain relatively less stable and consists of ~20-40 wt.% of biomass (Brunnet al., 2011). Lignin, structurally more complex, appears to be highly resistant to the thermal degradation. Lignin in biomass accounts for 18 to 40 wt.% (Lu et al., 2021). Biomass chemical composition is vital for biochar production as it affect the process of thermal degradation. Lignin-rich biomass produces better charcoal with higher calorific value. If the lignin content is relatively higher in biomass, it imparts higher biochar yield (Li et al., 2021). The biomass with higher cellulose and hemicelluloses contents gets pyrolyzed relatively faster than the biomass with higher lignin contents (Ojha et al., 2021).

Pyrolysis differ depending upon reaction conditions like speed of heat transfer to particles of feedstock, temperature (maximum), and residence time, by the means of slow and fast pyrolysis. Slow pyrolysis, the most widely used form for charcoal production (i.e., carbonization) generates biochar at relatively slow heating rates,low temperature ranges (300-600°C), and long residence time periods (hours-days) (Al Arni et al., 2018). For generation of ~20-40% charcoal/biochar, slow pyrolysis can be considered if operational conditions ensure reduction of gas and oil. Generally, under higher temperature, charcoal yield is lower. Production of biochar, highly functionalized in nature, is driven by low temperature andresidence time.Relatively higher contents of hydroxyl and carboxyl groups, in a way, are helpful for biochar in imparting enhanced soil CEC (Khan et al., 2021).

On the other hand, fast pyrolysis is targeted for production of bio-oil. As compared to slow pyrolysis, fast pyrolysis relies upon faster heating rates coupled with relatively short residence times. The ideal liquid yield can reach upto ~75% (Armynah et al., 2018). Feedstock, properly homogenized, if ground well (~2 mm) and ideally dried (moisture<10%), lead to high yields of bio-oil (Al Arni et al. 2018). Apart from bio-oil, the fast pyrolysis process also generates ~10-15% of biochar. Also, as it is conducted at relatively higher temperatures (>500°C), the aromaticity of biochar is relatively high (Das et al., 2021; Kim et al., 2012). Even for the same residence time, the atomic ratio of O to C (O/C) is lower in fast as compared to slow pyrolysis. The O/C ratio, in the order of 0.2 (i.e. highly stable) to 0.6 (i.e. highly functional) reflects biochar stability and functionality (Jindo et al., 2014).

3. Factors affecting the yield, composition and functionality

The yield of biochar was observed higher in low temperature conditions; however, as the temperature rises further, the yield gets decreased with increases in ash and C content (Zhang et al., 2018). The C content is enhanced by higher reaction temperature with H and O contents decreased (Nwajiakuet al., 2018). The composition of biochar varies with the feedstock type and temperature of the process. It has been found that element silicon (Si) dominates in biochar produced from by-products of rice plants (Daiet al., 2018). An increase in the temperature of pyrolysis increased the concentration of Ca, Mg and K (Mohamed et al., 2021). Moreover, amounts of volatile compounds decrease with increasing pyrolysis temperature.

Also, pH is one of the vital properties of biochar, which determine its application and usage as a soil amendment or as a remediation agent (Rehman et al., 2021). The pH of biochar influences mineral precipitation, mineralization of N and ion exchanges in soil (Fidel et al., 2017; Suliman et al., 2017). The feedstock type and temperature serve to regulate the pH of biochar with increasing pH with the increase of temperature (Kour et al., 2019).The pH increase, at relatively higher temperature, might be attributable to increasing concentrations of inorganic elements that are not pyrolyzed, coupled with surface-formed basic oxides at higher pyrolysis temperature

(Rehman et al., 2021). Acidic functional groups detachment during pyrolysis (e.g., hydroxyl, formyl or carboxyl) might also be one of the valid causes. During pyrolysis, removal of such functional groups, acidic in nature, change biochar to a more basic condition. Overall, an increase in pH contributes to greater degree of carbonization (Gwenzi et al., 2015).

The stability and C sequestration potential of biochar is determined by its chemical composition, structure, aromaticity, aromatic condensation degree and contents of the labile aliphatic compounds and volatile matter. The stability of the biochar is affected by the presence of minerals in soil (Yang et al., 2021). In case of low carbonized biochar, the concentration of volatile matter regulates the CEC. It has been observed that with aging, the capacity of anionic exchange also decreases (Cao et al., 2019). Hard Lewis acid adsorption takes place through ion exchange, e.g., via carboxylic functionalities, whereas soft Lewis acid adsorption occurs through mechanisms of the cation-π bonding (Huang et al., 2021). It was noticed that the sorption capability is governed by the surface area and aromaticity-porosity. Porosity and surface area determine the soil's water holding capacity (Dhamodharan et al., 2020). It was observed that pH, porosity, surface area, sorption properties and presence/absence of hazardous/beneficial compounds regulates the biota interactions (Sun et al., 2015; Rwizaet al., 2018).

4. Biochar as tool for environmental sustainability

Biochar, being a recalcitrant C-source, upon soil applications helps in slowing down native soil organic C (SOC) turnover and enhancing N fertilizer use efficiency, thus, resulting into reduction in GHGs emissions (Bhattacharyya et al., 2020). Biochar is useful in enriching SOC contents, enhancing beneficial biological activities, and increasing availability of nutrients (Bhattacharyya et al., 2021). It has been observed that its application to soil leads to improvement in soil fertility, improved soil water holding capacity, enhanced crop productivity, long-term betterment of soil health, soil C sequestration, pest and disease control, bioremediation of heavy metals in soil, degradation of dyes, and conversion of biowaste. Some of the major aspects are further discussed below.

4.1. Biochar for soil remediation

The amendments of soil with biochar delivers numerous benefits in terms of improvement in soil fertility, CEC, reduced nutrient leaching, availability of useful microbes and decreased emissions of greenhouse gases. Figure 1 presented the various applications of biochar with respect to soil. The in-detail analysis of biochar's importance in soil restoration and sustainability of the environmental (Table 1) is presented below.

4.1.1. Soil property and crop productivity

Excessive application of chemical fertilizers in the agricultural fields leads to nutrient leaching and loss of nutrients due to run-off (e.g., N and P) to water bodies in close proximity resulting in eutrophication, soil fertility reduction and soil acidification (Khan et al., 2021; He et al., 2021). Biochar amendments in soil help to increase SOC contents and facilitate the beneficial microbial populations and their maintenance in specific niches in soil (Sun et al., 2021; Hua et al., 2021). Biochar acts as a growth promoter for soil microbes by providing favorable conditions in terms of aeration, moisture, pH balance and more importantly the organic substrates. Biochar significantly affects the metabolic activities of the soil microbes and modifies their diversity and abundance (Palansooriya et al., 2019). Soil modified with biochar exhibits improved physico-chemical properties such as CEC, reduced leaching of soluble macronutrients, improve soil's water holding capacity. It has been observed that weathered tropical soils modified with biochar possessbetter soil fertility and crop productivity (Morales et al., 2021). A positive crop response was observed between the incorporation of biochar amended soils and crop production.In case of dry land, crops planted to acidic and sandy soils, crop responses were relatively greater to biochar amendment. Non-irrigated biochar mixed with soil can be utilized for the production of crops because of its capacity to retain more rainfall water in comparison to unaltered soil (Liu et al., 2017). Kiln-derived and gasifier-derived biochar of various feedstocks such as coffee and rice husks, maize cobs, groundnut shells and eucalyptus wood, were compared (Deal et al., 2012). It was observed that, the soil modified with gasifier-derived biochar possess higher yields of crops in comparison to the soil amended with kiln-derived biochar (Deal et al., 2012). Biochar, having high ash contents, helps in reducing soil acidity, increasing contents of some essential elements (e.g.,Mg, Ca and K) and decreasing availability of Al (Gray et al., 2014). An improvement in water retention capacity was also noticed due to the enhanced surface area (Kookana et al., 2011). The addition of biochar in sandy soil drastically enhances the water holding capacity by increasing the gaps in micropores and providing strong hydrophobicity, which is beneficial in drought like conditions (Li et al., 2021). The higher specific surface area of biochar is related to the presence of porous structure, which in turn acts as surplus capillaries, thereby favouring water retention in soil. When soil acidity decreases, there is an increase in soil capacity for exchanging ions. The effect of biochar on soil characteristics and plant growth are regulated by its type, application rate, type of soil-crop andtime lapse after application. It has been observed that the residence time in soil, its availability and aging process are vital factors.

4.1.2. SOC sequestration and C-use efficiency in agriculture

Biochar's ability to slowly degrade in soil helps gradual building up of SOC (i.e. gradual rise in organic C status) over time. The organic C, being tightly bound to soil particles, leads to relatively lower emission of CO_2 from soil to atmosphere. Hence, the addition of biochar in agriculture helps abate GHGs emissions and climate change (Liu et al., 2017).With the incorporation of biochar in the soil, it might become C sink for long-term C storage (Domingues et al., 2017). The soil type and quality also determine biochar's mean residence time. Biochar contributes to building up a refractory SOC pool and has positive implications on SOC dynamics (Wang et al., 2016). Agriculture can act as a net source/sink for GHGs depending on the management practices (Neogi et al., 2020). Agricultural management practices that can foster soil C sequestration are, in a way, helpful in mitigating climate change. It has been found that amendment of soil imparts protection to SOC from utilization (Bhattacharyya et al., 2020). The biochar's high surface area and porosity facilitates the reduction in microbial activity and regulates the stabilization of native SOC. Incorporation of biochar minimizes the CO_2 emissions from soil by altering its characteristics and microbial diversity. It can help increase microbial biomass in soil and increased SOC accumulation with C-use efficiency.

Keenan et al. (2016) has mentioned about the importance of biochar addition to wetland peat soils in decreasing GHG emissions, while studying the implications of biochar C on wetlands and emanation of agricultural soil C, in North Carolina, USA. A reduction (45.2–54.9%) in the emission of CH_4 was reported in Japan, by the incorporation of biochar C paddyrice wetlands (Pratiwi and Shinogi, 2016). In a study, biochar modified with mineral ions (Fe/Ca) has remarkably improved the stability of aggregated soil and its C sequestration ability, present in coastal wetland area. A shift in the microbial community which prefer labile-C to the microbial community preferring recalcitrant-C was also noticed in case of soil amended with Fe-modified biochar (Liu et al. 2020). Overall, the biochar's application is considered as 'C negative', because of the conversion of C sink to C storage, which could be maintained for an extend period (Khadem et al., 2021; Brassard et al., 2017).

4.1.3. N leaching and utilization

Overuse of agricultural N fertilization (mainly urea) in croplands is of grave concern, as it leads to water quality-related problems and induce emissions of nitrous oxide (N_2O) from soil-crop continuum to atmosphere (González et al., 2015). Low N use efficiency (~30-40%), risk associated with N leaching, N_2O emissions and ammonia volatilization have been challenging environmental sustainability across the globe (Li et al., 2018a). Therefore, upon fertilizer application, reduction in N release with enhancement in N utilization by plants is of vital importance for sustainable agriculture. Biochar's enhanced surface area and porosity help retain nutrients (e.g., N) in soil and soil solution as well (Li et al., 2018b). Feedstock types and pyrolysis temperature govern the N retention capacity of biochar. Biochar amendments with chemical N fertilizer offers relatively slow N release from the agricultural soil (Wen et al., 2017). It was observed that the minerals bentonite and sepiolite promote the biochar-urea aggregation and facilitate the adsorption for enhancement of N retention further. Moreover, biochar produced from agro-wastes, might be useful as a blending material with urea to develop organo-mineral combined urea to replace exclusive form of mineral urea, decreasing the usage of N. More advanced research needs to be performed to have an idea of potential impact of biochar mixed with urea on the N process in agricultural systems. It has been observed that biochar affected soil N cycling, the rates of nitrification process, adsorption of ammonia, and increased in storage of ammonium through improving and enhancing soil CEC (Gupta et al., 2019). Its application helps to reduce leaching of nitrate and gaseous N losses.

4.1.4. Controlling pests

The process of biotic stress control and maximization the crop production need to be eco-friendly and sustainable. The incorporation of biochar as an organic soil amendment (OSA) fits with this context. Biochar's application enriches beneficial soil microorganisms and triggers the suppression against pathogens. Soil suppression inhibits the development of diseases associated with nematodes, fungi, bacteria and viruses. This is attributable to stimulation of activity of soil biota, increase in favoured biocontrol agent population and reduction in pathogen inoculum potential (Chung et al., 2021). Biochar suppresses soil's pathogenic activities and infection-causing capabilities (e.g., reducing infectionsfrom plant parasitic nematodes). Also, an increase in free living nematode population is considered beneficial for soil health (Wu et al., 2020). Biochar decreases the negative influence of pesticides on the environment via pesticide absorption and adsorption. It helps reduce pesticide bioavailability attributable to its greater surface area and higher porosity. It also protects the plant roots in soil from phytotoxic compounds released by other plant roots, by plant residue decomposition and soil amendment in form of agro-waste products (Xia et al., 2022).

4.2. Bioremediation of environmental pollutants

Biochar has been widely employed for the elimination of numerous hazardous contaminants such as heavy metals, toxic azo dyes, and pharmaceuticals and personal care products (PPCPs). A brief description of the reports available on the role of biochar on the elimination of these contaminants is discussed below.

4.2.1. Removal of Heavy metals

The heavy metals adsorption and removal has been widely reported by the application of biochar (Table 2). The adsorption mechanisms of heavy metals on biochar mainly involve physical-adsorption, ion-exchange interactions, electrostatic attraction, functional groups combination, surface complexation and precipitation (Li et al., 2019). Each metal has a specific mechanism of adsorption and the relevant properties of biochar further affect the adsorption characteristics. Numerous reports available on the basis of characterizations such as SEM, TEM, FTIR and XRD analysis have also revealed the high sorption efficiency of biochar for heavy metals (Xiang et al., 2019; Yaashikaa 2020). The chestnut shell derived biochar for arsenic adsorption was increased from 17.5 mg/g to 45.8 mg/g by the activation using magnetic gelatine. The modification enhanced the surface area and improved the magnetic biochar characterization (Zhou et al., 2017). Xiao et al.(2019) reported the removal of Cr(VI) and Cu(II) from the aqueous solution using the chitosan based combination of magnetic loofah biochar (CMLB). In this study, 40% CMLB showed a maximum adsorption of 30.14 mg/g and 54.68 mg/g for Cr(VI) and Cu(II), respectively. Rice husk ash biochar was applied for the elimination of heavy metals like Pb^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+}, Zn^{2+} and $Cd^{2+}$with the removal efficiency of 99.09%, 65.95%, 7.98%, 33.93%, 30.48% and 29.02%, respectively (Yu et al., 2018). The biochar colloids-mycelial pellets (BC-MP) were prepared to study the adsorption of heavy metals. In this study, batch experiments were performed with the model contaminant Cd(II). The BC-MP displayed enhanced (57.66%) removal efficiency in comparison to BC (5.45%) and MP (38.45%) (Bai et al., 2020). In another study, sewage sludge biochar was reported for the removal of Cu^{2+} (99.63%), Zn^{2+} (98.06%), Mn (79.6%) (Zhou et al., 2017). Biochar delivered a huge potential in the elimination of heavy metals and thus play important role in the treatment of water pollution by transforming toxic heavy metals into their simplest form, and hence contributed in the environmental sustainability.

4.2.2. Degradation of dyes

Effluents from dyeing industries into rivers or lakes pose a major environmental risk. Dyes are considered as contaminants, being categorized as carcinogenic/teratogenic, thus causing damage to the ecology. The dye-containing wastewater is known to be transformed into toxic elements such as dioxin (Khan et al., 2021). Biochar is well reported for theadsorption and catalytic degradation of dyes, because of the availability of abundant functional groups and relatively large surface area (Table 2). The treatment of dyes with sulfide-modified biochar can be a viable and effective solution. Utilizing relatively low-cost, environment friendly and varied biochar materials from agro-wastes such as rice chaff, corn and bean stalks, have become promising for minimizing the dye concentration. Also sulfides, along with the biochar, have the capacity to decompose and transform the oxidizing dyes.

The dye adsorption capacity and efficiency of biochar varied with dye concentrations, pH and temperature (Ahmad et al., 2020; Han et al., 2021). The adsorption of methylene blue dye present in wastewater was studied using the biochar modified with nickel and the adsorption capacity was calculated as 479.49 mg/g at 20°C (Yao et al., 2020). The adsorption was initially high when the concentration of methylene blue was limited because of the large number of active sites available for adsorption on the biochar. Ahmad et al. (2020) also studied the adsorption of methylene blue by the application of biochar derived from rice husk, cow dung and sludge with the adsorption capacity of 97.0-99.0%, 71.0-99.0% and 73.0-98.9%, respectively. According to Ganguly et al., 2020, biochar made from rice husk has eliminated 99.98% of the malachite green dye from wastewater. Similarly, Abd-Elhamid et al. (2020) reported the removal of methylene blue (94.45%) and crystal violet (92.70%) using rice straw biochar. The highly porous structure of biochar derived from rice husk and cow dung has efficiently absorbed the 66-99% congo red dye (Khan et al., 2020). Metal salt modified agro-waste biochar achieved a high adsorption capacity of 96.8% for congo red dye as compared to native biochar (Nguyen et al., 2021). The highest sorption of malachite green dye was 3000 mg/L, which was achieved after five repeated cycles using sugarcane bagasse biochar (Vyavahare et al., 2021).

4.2.3. Removal of pharmaceutical and personal care products (PPCPs)

Pharmaceuticals and personal care products (PPCPs) are a diverse category of organic pollutants used in medical and personal care of humans and animals. PPCPs are recognized as emerging pollutants because of their adverse effects on human and aquatic life and have been widely reported in domestic/hospital and industrial wastewater (Yang et al., 2017; Chaturvedi et al., 2021; Keerthanan et al., 2020). The wild plum kernels derived biochar was functionalized with potassium hydroxide and utilized for the removal of naproxen (NPX), which is an ionizable pharmaceutical component. It was observed that the interactions such as electrostatic interaction, electron-donor-acceptor (EDA) and H-bonding, were mainly responsible for achieving maximum adsorption of 73.14 mg/g (Paunovic et al., 2019). Keerthanan et al. (2020) mentioned that *Gliricidia sepium* biochar (GBC) produced at 700°C displayed highest adsorption capacity of 16.26 mg/g for caffeine. They demonstrated that a lower pH range, high aromaticity and larger surface area, were the important factors for gaining maximum adsorption of caffeine. In a study, Pinyon Pine Juniper (PJ) wood biochar was utilized to eliminate around 10 contaminants of emerging concern from treated wastewater and the reclaimed water was further utilized for the purpose of irrigation. It was observed that among the 10 emerging contaminants, diphenhydramine (DPH), trimethoprim (TMP) and fluoxetine (FXT) were completely removed by the action of biochar (Yanala et al., 2020). In a report, a modified manganese oxide composite (MMB)-based biochar and raw biochar were applied for the elimination of fluoroquinolone antibiotics, considering norfloxacin, ciprofloxacin and enrofloxacin as the model compounds. High adsorption capacities of 6.94, 8.37, and 7.19 mg/g of MMB were obtained for the norfloxacin, ciprofloxacin and enrofloxacin, respectively (Li et al., 2018). In another study, the magnetic biochar (M-BC) derived from the *Astragalus membranaceous* residues was utilized for the efficient and cost-effective removal of ciprofloxacin, with an enhanced adsorption capacity of 68.9 mg/g (Kong et al., 2017). Kenaf derived biochar has been reported for the elimination of 90% triclosan with 4 g/L biochar. The biochar possesses enlarged specific surface area and enhanced aromatic moiety (Cho et al., 2021). The organic waste present in sewage sludge was consumed for the cost-effective synthesis of engineered biochar. The PPCPs such as diclofenac, triclosan and naproxen were eliminated with an adsorption capacity of 92.7 mg/g, 113 mg/g and 127 mg/g, respectively. The π–π interactions and H-bonding among the functional groups of triclosan and biochar were considered for achieving maximum adsorption of PPCPs (Czech et al., 2021). Similarly, the antibiotics tetracycline and doxycycline were removed by the iron-based sludge biochar with an adsorption capacity of 104.86 mg/g and 128.98 mg/g (Wei et al., 2019). Biochar based catalysts were also reported for the catalytic degradation of PPCPs which includes metal-doped and metal-free biochar (Do Minh et al., 2020). Hence, biochar-based removal of PPCPs can be considered as a budget friendly, efficient and eco-friendly approach, desired for achieving sustainable development goals (Table 2) (Zhu et al., 2022).

4.3. Bio-waste to Bio-energy production

The co-production of biofuels (syngas and bio-oil) along with biochar from biomass during pyrolysis has been extensively studied. However, the amount of biofuels and biochar varied with the process conditions, e.g., temperature, feedstock type, heating rate, and residence time. The potential of biochar has been verified for the enhanced synthesis of biofuels and compounds involved in the generation of bioenergy such as biogas, bio-oil, hydrogen (H_2), methane, electricity, biodiesel and medium-chain carboxylates (Table 2) (Sun et al., 2020, Liu et al., 2017). Biochar assisted the generation of biofuels by acting as the biocatalyst, providing the large number of acidic sites, altering the biotic as well as abiotic conditions, facilitating the growth of acetogenic and methanogenic bacteria and by the formation of biofilms. This section reviews biochar's contribution to provide an affordable and clean energy and promotes sustainability. Biochar serves as a cost-effective by-product of biorefinery with rich physiochemical properties, which reduces the dependence on expensive and hazardous chemicals for the generation of biofuels (Sun et al., 2020). The processing of pyrolysis products bio-oil and syngas were utilized for the production of bio-diesel and electricity, respectively. A certain amount of energy and the process heat obtained from the pyrolysis by-products can be consumed to offset fossil carbon emissions (Woolf et al., 2010).

Functionalized biochar has a considerable potential to be used as direct catalysts or catalyst supports in biomass upgrading processes (Shukla et al., 2021). A high yield (88%) of biodiesel was obtained from cooking oil by the catalysis of acid functionalized biochar (Lee et al., 2017a). The pomelo peel biochar was employed as a carbon catalyst support, which showed a high yield (>82%) of biodiesel and reusability of 8 cycles (Zhao et al., 2018). The metallo-engineered biochar such as Mg–Ni–Mo/MPC (modified pyrochar), $WO_3/ZrO_2/Al_2O_3$ and TiO_2/ZrO_2 with Al_2O_3/ZrO_2 were consumed as catalysts for the synthesis of bio-oil and ester (biodiesel) (Pirbazari et al., 2019, Lee et al., 2017b, Shukla et al., 2021). The presence of large number of acids cites (–SO_3H groups) on the biochar's surface are known to be responsible for the high yield of biodiesel. Therefore, biochar with high porosity and surface areas is suitable for adding acidic groups (Chen et al., 2017). The synthesis of esters from the processing of free fatty acids (FFA) catalysed by the active biochar was reported to be consumed as biofuels through esterification (Shukla et al., 2021).

The composites of biochar were consumed for the storage of energy by the preparation of electrodes. The high costs of conventional electrode materials such as carbon nanotubes and graphene led to search an eco-friendly and inexpensive source of C-rich material. Biochar has the potential to be considered for the storage of electrochemical energy by the preparation of electrodes and further applied in fuel cells, Li-ion battery and supercapacitors (Cheng et al., 2017). A pinecone biochar fabricated with polyoxometalate (POM) possessed high redox activity and areal capacitance, which was approximately 2.5 times higher in relation to the unmodified carbon (Genovese et al., 2017). The engineered electrodes such as biochar based activated carbon (BAC) derived from corn-straw, modified with KOH, were applied in microbial fuel cells (MFC) for transforming chemical energy into electrical energy (Wang et al., 2017). In a report, a functionalized carbon cloth (CC) was associated with a varied concentration of biochar in a dual chambered MFC and the system displayed a high-power density and suitable decrease in chemical oxygen demand (COD) (Wang et al., 2018; Manyà et al., 2021).

The amendment of anaerobic digesters with biochar enhanced the production of hydrogen, methane and medium chain carboxylates (Sun et al., 2020; Shen et al., 2016; Sharma and Melkania, 2017). The production of H_2 was reported to be enhanced by four times with the addition of biochar in a municipal solid waste based anaerobic digester (Sharma and Melkania, 2017). Biochar aided the modification in the composition as well as synthesis of volatile fatty acids (VFAs) (Sun et al., 2019). The application of biochar played a significant role in enhancing H_2 production by inhibiting ammonia, supporting the formation of biofilm, nutrient supply and facilitating pH buffering (Zhang et al., 2017). In this way, biochar enhanced the production of H_2 by altering the biotic as well as abiotic conditions in anaerobic digesters.

The production of biogas was reported to be enhanced by the addition of white oak (WOBC), corn stover (CSBC) and pinewood (PWBC)-derived biochar in the anaerobic digesters. The addition of biochar facilitates the growth of acetogenic and methanogenic bacteria, and easy removal of CO_2, H_2S and NH_3. The incorporation of biochar derived from pine wood and oak wood, enhanced the content of methane in biogas by 92.3% and 79.0%, respectively (Shen et al., 2017; Shen et al., 2016). An improvement of 31% and 10% in the yield of H_2 and CH_4 was observed due to the supplementation of biochar in a carbohydrate food waste mediated anaerobic digester (Sunyoto et al., 2016). The biochar-based enrichment of anaerobic digestion has also been reported to enhance the synthesis of medium-chain carboxylates (MCC). The MCCs caprylate (C8) and hexanoate (C6) are considered as important chemicals that can be further transformed into biofuels. The presence of pine wood-based biochar in the digester, also increased the production of hexanoate and caprylate by 50% and 100%, respectively (Liu et al., 2017).

The Acetone-Butanol-Ethanol (ABE) fermentation was also found to be benefited by addition of biochar. The ABE fermentation can replace petro-chemical pathway for the synthesis of acetone and butanol. Biobutanol is a popular biofuel with the ability to replace gasoline without making any making any change in the fuel distribution mechanism and available engines (Brito and Martins, 2017). Switchgrass (SGBC), red cedar (RCBC), poultry litter (PLBC) and forage sorghum (FSBC) derived biochar, were added to the medium in place of costlier buffer 4-morpholineethanesulfonic acid (MES). The study demonstrated that the supplementation of biochar resulted in 84% decrease in the cost of medium (Sun et al., 2019). An enhanced production of butanol and hydrogen was investigated by the incorporation of biochar in *Clostridium beijerinckii* cultured ABE fermentation. Biochar assisted microbes to form biofilm and efficiently consumed substrate (Wu et al., 2019). The biochar's addition in syngas fermentation has made a huge reduction in the cost of nutrients by avoiding expensive chemicals (Sun et al., 2020).

4.4. Biochar for Climate Change Mitigation

4.4.1 GHGs emissions reduction and neutral carbon footprint

Regarding the concentration of C in biochar, a major part is recalcitrant and smaller portion is labile in nature, affecting the soil C/N ratio. Biochar incorporation stores biogenic C in soil and offsets C emissions by burning of fossil fuel. Studies reported that the application of biochar has the capacity to decrease the emissions of CO_2 from soil to atmosphere; thereby minimizes CH_4 and N_2O emissions as well, thereby, taking strides towards mitigating green house effect. It was observed that the soil modified with biochar showed reduction in the emissions of CO_2, while in few other studies, no significant effect on soil CO_2 efflux was mentioned (Chung et al., 2021). The incorporation of biochar in paddy soil has decreased the emissions of CO_2 and CH_4 (Yin et al., 2021). The soil modified with biochar for the purpose of rice cultivation has been reported to reduce CO_2 emissions (Bi et al., 2021).

The technique of carbon footprinting has been widely employed for the calculation of GHG emissions from the agricultural productions (Cooper et al., 2021). The phrase "carbon footprint" represents the amount of GHG produced by a variety of activities and goods. Carbon footprint has the potential to be used to analyse and compare the GHG emissions of various agricultural products, as well as to identify the areas where environmental efficiency may be improved (Xu et al., 2019). In a study based on Mediterranean wheat, relatively very less emission of CO_2 and CH_4 was observed because of the action of biochar (Liu et al., 2011). Short-term pilot scale study on boreal agricultural soil also reported a low CO_2 flux upon the amendments with the biochar, whereas an increase of ~96% CH_4 uptake rate was observed in case of treated soil in relation to the untreated soil (Zimmerman 2010). The nitrated production mediated by the nitrifying bacteria has been facilitated by the incorporation of biochar and synthetic N, which provides the labile C and ammonium. Denitrifying bacteria transforms nitrate into N_2O/N_2 at intermittent aerobic and anaerobic conditions. Thus, numerous studies have reported the suppressive effect of biochar for the emissions of N_2O. The incorporation of biochar in soil also decreases the intensity of GHGs per unit of agricultural product by decreasing the addition of labile C and N-fertilizer, while maintaining the productivity (Qian et al., 2014). As reported by Woolf et al. 2010, the proposal of global implementation of biochar can reduce 1.8 Pg CO_2-Ce per year of annual emissions which counts approximately 12% of current anthropogenic CO_2 carbon equivalent (CO_2-Ce) emissions, this made the total net emissions of 130 Pg CO_2-Ce in a century. Another intriguing finding was that potassium-doped biochar enhanced the carbon sequestration capacity by 45%. This increases the worldwide biochar mediated carbon sequestration capacity with $\geq$ 2.6 Gt CO_2-Ce per year (Masek et al., 2019). As per the International Biochar Initiative (IBI), the O/C ratio of biochar played major role in the stability of biochar in soil (Budai et al., 2013). Also, ~79.6% of biochar C was reported to persist for more than hundred years (Dharmakeerthi et al., 2015). Recent reports on the application of biochar as an ingredient for preparation of building materials are gaining attention. Biochar emerges as a carbon negative source that has been incorporated in suitable proportions with the cement for construction purpose and acts as a partial replacement of cement. It is reported that biochar enhances the mechanical strength and thermal properties of the concrete, thereby reducing the CO_2 emissions (Mensah et al., 2021).

Biochar offers wide range of potential applications, thus it is also necessary to discuss the environmental risks associated with it. The biochar's surface properties such as presence of various functional groups, variation in pH and oxidation of aromatic C-ring, sometimes resulted in the synthesis of hazardous components (heavy metals, dioxins, polycyclic aromatic hydrocarbons (PAHs) and free radicals). The biochar derived from the crop *Miscanthus* has been reported to possess hazardous metals that enters into the environment via leaching (von Gunten et al. 2017). Hale et al. 2012 has detected the presence of dioxins during the preparation of biochar from the food wastes, pine wood and milk fertilizer. The concentration of dioxin and toxicity equivalency quotient (TEQ) are the important factors for determining the risk associated with the synthesis of dioxins from the biochar. The highly toxic compounds PAHs and their precursors, especially for plants and microbes, are present in various environmental mediums. Biochar derived from plants such as hemp are known to contain high mutagen content. A study conducted on over 50 biochars showed that the concentration of PAHs is higher in biochars produced with fast pyrolysis process than the slow pyrolysis, and flash evaporation is also responsible for the enhancement of biochar's PAH content (Hale et al. 2012). Also, the release of metals such as Ca, Al and Ba during the process of pyrolysis performed at high temperature, facilitates the leaching of PAHs. The formation of free radicals (e.g. hydroxyl free radicals and semiquinone free radicals) during the process of pyrolysis leads to the damage of cells and organs (Shen et al. 2022).

5. Biochar for Boosting Circular Bio-economy

Crop residues are post-harvest left-over items.For example, rice production at global scale alone generates ~800 million tons straw annually. Here lies the importance of availability of scientifically designed rational strategies for effective and fruitful use of nutrient rich enormous biomass and its proper degradation. Cost-effective and environment friendly utilization of agro-wastes are accomplished by producing biochar, biogas and concomitant generation of renewable energy (Khan et al., 2021). From an environmental sustainability point of view, it is crucial that biomass is utilized in such a way ensuring ultimate zero waste and zero harm to environment (Bhattacharyya et al., 2020). Biomass can be transformed to functional carbonized product via biochar formation. Identifying and optimization of effective biomass, proper technology for biochar production, dosages and applications in crop fields might ensure significant increment in soil C contents and its stocks along different soil profiles, curbing GHGs emissions to the atmosphere from the soil-crop system (Atkinson et al., 2018). Hence, biochar production technology from biomass waste and its wide applications in agriculture, remediation and generation of energy, look promising as a valuable approach. Thus, maintaining soil health, sustainable crop production, renewable energy production, better environment management, in a way fostering a circular bio-economy in context of climate amelioration (Figure 2) (Ilyas et al., 2021).

It has been observed that recycling oflarge quantity of bio-wastes and its subsequent applications in cereal crop fields does not provide a positive economic return on investment. In this context, functionally enhanced biochar, even in small quantities, might prove to be an effective solution in terms of low-cost and high efficiency. It is noteworthy to mention here about novel nano-biochar material that can help in tackling soil metal contaminations (Li et al., 2020; Joseph et al., 2013). Biochar, in small amounts also, when judiciously blended with chemical nutrients, have been found to manifest greatly enhanced agronomic use efficiency of nutrients and growth promoting activities in plants. Transiting from mineral fertilizer usages towards boosting more and more green agriculture, the application of this biochar-based compound fertilizer (BCF) technology could be potentially helpful (Qian et al., 2014). Moreover, BCF technology might be helpful in facilitating a net income rise of farmers via increases in crop yield, reduced usages of chemical fertilizers and GHGs emissions from the crop-soil system (Zheng et al., 2017; Hu et al., 2019). As biochar is usually produced from bio-waste, therefore, the waste materials are being continually reused and utilized. Hence, standardized and optimized biochar production technology and application are considered as environmentally sustainable and economically viable intervention strategy for abating climate change.

6. Biochar Functions towards Attaining SDGs

The waste derived cost-effective synthesis of biochar and its utilization for the enrichment of soil, treatment of wastewater along with the generation of bioenergy, in one way or the other, contributed to achieve the sustainable development goals. For achieving SDG 1 (no poverty), cost reduction and reliance on external resources (e.g., use of biochar from biomass feedstock) along with rise in crop productivity will be helpful for farmers becoming self-sufficient and have monetary gain as well. For SDG 2 (zero hunger), to increase the crop yield in degraded soils, biochar, in form of mineral rich composite as slow-release fertilizers, might play useful role for wide applications (Gao et al., 2020). Food security will get boosted, attributable to higher yields and greater resilience of agro-ecosystem. For SDG 3 (good health and well-being), through biochar application to soil and crop yield increases as well as remediation of soil and purification of water, nutritional health of people can be accomplished. Biochar with microbial inoculation and iron-biochar application to soil can be helpful in immobilizing metals and degrading organic contaminants (Meili et al., 2019). For SDG 6 (clean water and sanitation), biochar has been instrumental in adsorbing soil pollutants, avoiding leaching andwater pollution. Efforts have been made for improving sorption of contaminants (Atinafu et al., 2020). For SDG 7 (affordable and clean energy), feedstock biomass pyrolysis acts as source for relatively cheaper, affordable renewable energy. Biochar composites were utilized for the cost-effective solution for the generation of bioenergy by replacing expensive chemicals, thus helps in achieving SDG 7 (Chen et al., 2020). For SDG 8 (decent work and economic growth), achieving SDGs 1 and 2, is associated with the farmers' living condition improvement in rural areas.

Developing cost effective (low-cost) pyrolyzer technologies for use of rural small-holder farmers (e.g., earth-dug), helps achieve SDG 9 (industry, innovation and infrastructure) (Hamid et al., 2020). For SDG 10 (reduced inequality), biochar can help small holder farmers in rural areas becoming self-sufficient and improving women's health attributable to clean cooking technology; and will increase income of female, leading to less hunger, poverty, thereby, minimizing inequalities between rural and urban places. For SDG 11 (sustainable cities and communities), urban abandoned contaminated land remediation through use of composites of iron-biochar, clay-biochar might be feasible (Wang et al., 2020). Biochar functions in urban planting can prove to be helpful in achieving this SDG. Urban plantations help adapt cities facing future extreme weather events such as heat waves. Also, biochar is reportedly known to contribute in the sustainable drainage system in an urban area in China (Chen et al., 2021). Biochar production through biomass pyrolysis can change the consumption of C-rich non-renewable (SDG 12, responsible consumption and production) and can foster ground based C storage (SDG 13, climate action) (Kammann et al., 2017). For SDG 12, increasing yields of crops can be achieved with biochar soil application. Biochar usage in animal husbandry might be helpful in reducing antibiotics use, resulting into positive impacts on animal and human health (Shalini et al., 2020). For SDG 13 (climate action), relatively high recalcitrant nature of biochar organic C, and reducing emissions of N_2O, CH_4 and CO_2 from amended soils lead to climate amelioration (Ahmad et al., 2019). Increasing agro-ecosystems resilience helps in adapting and mitigating future anticipated climate change effects. Minerals addition during pyrolysis or iron-biochar composites application can enhance C stability and negative priming effects (Liu et al., 2020; Hou et al., 2020). For SDG 15 (life on land), biochar addition, through improvement of soil fertility and decrease in soil-water pollutants, can provide habitats for beneficial soil microorganisms, ensuring better soil health. Biochar technologies, its varied applications and potentials, if revisited and reconciliated through the lens of reducing poverty and concomitant preservation of environment, turns out to play prominent role in attaining SDGs (Yu et al., 2020).

7. Socio-economic Impact and Way Forward

Biochar has received global scientific attention as a promising agent for negative emission technologies (NETs), as well as a potential matter to reduce toxic elements in the environments for sustainable environmental remediation (Hansson et al., 2021). Biochar applications to soil have been found to decrease the usage of chemical fertilizer and parallelly increasing the crop yield. Its application to soil helps curtail GHG emissions to atmosphere via soil C storage for relatively long-term scale. Even coupled biochar-bioenergy production systems played an significant role in reducing consumption of fossil fuel energy (Yumin et al., 2021). Various researchers have emphasised the fact that biochar is a promising economic material for its applicability towards environment sustainability. Nearly 60% of nitrogen fertilizers are wasted due to run off, leaching, and vaporization. This lost nitrogen increases the fertilizer cost as well as cause the serious environmental issue of greenhouse gas emission, eutrophication as well as oxygen loss (Cen 2021). The biochar based fertilizers have proved to be an effective alternative over conventional fertilizers. The functionalized biochar provides a nutrient-rich environment to the soil and subsequently promotes organic farming. The modification in biochar based fertilizer with polylactic acid has demonstrated 70% crop production efficiency over conventional nitrogen fertilizers that have 30-40 % efficiency (Cen et al., 2021). The evidence from the field study indicated that a urine-enriched biochar enriched the crop production yield by 60% in rural areas of Bangladesh (Sutradhar et al., 2021).

Praveen et al. (2021) reported that the biochar derived from feed stocks such as coconut shell (CS), groundnut shell (GS) and rice husk (RH) costs about 0.61 USD, 0.57 USD and 0.57USD per kg, respectively. The study indicated that these biochar's can be considered as economic adsorbents, as their cost for adsorption was as low as 0.061 USD, 0.012 USD, 0.013 USD (CS, GS, RH) for the elimination of 1g dye from water (Praveen et al., 2021). The production, application and storage of biochar is considered as aneminently carbon negative, with an approx. sequestration of 0.3–2 Gt CO_2 per year by 2050. The methods such as direct air capture (CO_2), forestation, soil based C sequestration, wooden based building materials and biochar, showed atmospheric carbon removal costs ranging from 13.78 to 1233.5 USD per ton CO_2. In which, biochar's cost lies between 71.67 to 180.54 USD per ton CO_2. This data demonstrates the need of large scale production of biochar (Fawzy et al., 2021). It is reported that renewal energy and C-credits can help in reducing the minimum selling price of biochar and bio-based fuels. Sahoo et al. (2019) suggested that woodchips briquettes, torrefied woodchips briquettes and biochar, are economical systems for providing valuable products and contributes in decreasing GHG emissions and wildfires. Also, the lack of knowledge among farmers regarding the policies and application biochar in soil enrichment is the major area that needs to be focused and improved to enhance the economic benefits of biochar. Hence, Biochar has emerged as an economic alternative over various conventional methods for mitigating toxicity and achieving environmental sustainability.

8. Conclusion

The need for an economical, environment friendly, highly efficient approach, to manage the huge solid waste, leads to the development of biochar-based strategies, which offers a wide range of benefits including enhancing overall status of soil health and productivity, improving sustainability of agricultural systems for food production and biofuel production.The properties of biochar/ engineered biochar which include high specific surface area, large pore size, easy separation of engineered biochar and abundant functional groups could be customized to gain high adsorption capacities. Sustainable development evolves through continuous transformation and biochar holds a solution place in attaining circular bioeconomy and achieving UNSDGs. Therefore, certain future prospects can be considered for attaining SDGs within the timeframe:

- There is a scope of improvement in the search of novel feedstocks and development of more efficient methods involved in their transformation to biochar.
- The long-term implications of biochar-based technologies and their impacts on human life require more detailed studies.
- Climate amelioration, effect of different biochar production technologies with relation to varied feedstocks needs to be quantified and vetted for devising judicious intervention strategies in line with sustained crop productivity, improving soil health and environmental management, carbon footprint reduction and climate change abatement in food production.
- The methods of lifecycle assessment and cost-benefit analysis need to be combined for optimising the design of biochar production systems for its widespread implementation among farming communities.

Conflict of Interests

The authors declare that they have no conflict of interest.

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References

Abd-Elhamid, A. I., Emran, M., El-Sadek, M. H., El-Shanshory, A. A., Soliman, H. M., Akl, M. A., and Rashad, M. (2020). Enhanced removal of cationic dye by eco-friendly activated biochar derived from rice straw. Applied Water Science, 10(1), 1-11

Ahmad, A., Chowdhary, P., Khan, N., Chaurasia, D., Varjani, S., Pandey, A., and Chaturvedi, P. (2021a). Effect of sewage sludge biochar on the soil nutrient, microbial abundance, and plant biomass: A sustainable approach towards mitigation of solid waste. Chemosphere, 287, 132112.

Ahmad, A., Khan, N., Giri, B. S., Chowdhary, P., and Chaturvedi, P. (2020). Removal of methylene blue dye using rice husk, cow dung and sludge biochar: Characterization, application, and kinetic studies. Bioresource technology, 306, 123202.

Ahmad, A., Singh, A. P., Khan, N., Chowdhary, P., Giri, B. S., Varjani, S., and Chaturvedi, P. (2021b). Bio-composite of Fe-sludge biochar immobilized with Bacillus Sp. in packed column for bio-adsorption of Methylene blue in a hybrid treatment system: Isotherm and kinetic evaluation. Environmental Technology and Innovation, 23, 101734.

Ahmad, M., Ahmad, M., Usman, A. R. A., Al-Faraj, A. S., Abduljabbar, A., Ok, Y. S., and Al-Wabel, M. I. (2019). Date palm waste-derived biochar composites with silica and zeolite: synthesis, characterization and implication for carbon stability and recalcitrant potential. Environmental Geochemistry and Health, 41, 1687–1704.

Al Arni, S. (2018). Comparison of slow and fast pyrolysis for converting biomass into fuel. Renewable Energy, 124, 197-201.

Apicella, B., Tregrossi, A., Oliano, M. M., Russo, C., and Ciajolo, A. (2021). On-line fast analysis of light hydrocarbons, PAH and radicals by molecular-beam time of flight mass spectrometry. Chemosphere, 276, 130174.

Arif, M., Jan, T., Riaz, M., Fahad, S., Adnan, M., Ali, K., and Rasul, F. (2020). Biochar; a remedy for climate change. In Environment, Climate, Plant and Vegetation Growth, Springer, Cham, 151-171.

Armynah, B., Djafar, Z., Piarah, W. H., and Tahir, D. (2018). Analysis of chemical and physical properties of Biochar from Rice husk biomass. Journal of Physics: Conference Series 979, 012038.

Askeland, M., Clarke, B., and Paz-Ferreiro, J. (2019). Comparative characterization of biochars produced at three selected pyrolysis temperatures from common woody and herbaceous waste streams. Peer J, 7, e6784.

Atinafu, D. G., Wi, S., Yun, B. Y., and Kim, S. (2020). Engineering biochar with multiwalled carbon nanotube for efficient phase change material encapsulation and thermal energy storage. Energy, 216, 119294.

Atkinson, C. J. (2018). How good is the evidence that soil-applied biochar improves water-holding capacity?. Soil Use and Management, 34(2), 177-186.

Bai, S., Wang, L., Ma, F., Zhu, S., Xiao, T., Yu, T. and Wang, Y. (2020). Self-assembly biochar colloids mycelial pellet for heavy metal removal from aqueous solution. Chemosphere, 242, 125182.

Bhattacharyya, P., Bhaduri, D., Adak, T., Munda, S., Satapathy, B.S., Dash, P.K., Padhy, S.R., Pattanayak, A., Routray, S., Chakraborti, M., Baig, M.J., Mukherjee, A.K., Nayak, A.K., and Pathak, H. (2020). Characterization of rice straw from major cultivars for best alternative industrial uses to cut off the menace of straw burning. Industrial Crops and Products, 143, 111919.

Bhattacharyya, P., Bisen, J., Bhaduri, D., Priyadarsini, S., Munda, S., Chakraborti, M., Adak,T., Panneerselvam, P., Mukherjee, A.K., Swain, S.L., Dash, P.K., Padhy, S.R., Nayak, A.K., Pathak, H., Kumar, S., and Nimbrayan, P. (2021). Turn the wheel from waste to wealth: Economic and environmental gain of sustainable rice straw management practices over field burning in reference to India. Science of The Total Environment, 775, 145896.

Bi, Y., Cai, S., Wang, Y., Zhao, X., Wang, S., Xing, G. and Zhu, Z. (2020). Structural and microbial evidence for different soil carbon sequestration after four-year successive biochar application in two different paddy soils. Chemosphere. 254. 126881

Biswas, S., Mohapatra, S. S., Kumari, U., Meikap, B. C., and Sen, T. K. (2020). Batch and continuous closed circuit semi-fluidized bed operation: removal of MB dye using sugarcane bagasse biochar and alginate composite adsorbents. Journal of Environmental Chemical Engineering, 8(1), 103637.

Bolbol, H., Fekri, M., and Hejazi-Mehrizi, M. (2019). Layered double hydroxide–loaded biochar as a sorbent for the removal of aquatic phosphorus: Behavior and mechanism insights. Arabian Journal of Geosciences, 12, 1–11. https://doi.org/10.1007/s12517-019-4694-4

Brassard, P., Godbout, S., and Raghavan, V. (2017). Pyrolysis in auger reactors for biochar and bio-oil production: a review. Biosystems Engineering, 161, 80–92.

Brito, M., and Martins, F. (2017). Life cycle assessment of butanol production. Fuel, 208, 476-482.

Bruun, E. W., Hauggaard-Nielsen, H., Ibrahim, N., Egsgaard, H., Ambus, P., Jensen, P. A., and Dam-Johansen, K. (2011). Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil. Biomass and Bioenergy, 35(3), 1182-1189.

Budai, A., Zimmerman, A. R., Cowie, A. L., Webber, J. B. W., Singh, B. P., Glaser, B., Masiello, C.A., Andersson, D., Shields, F., Lehmann, J. and Camps Arbestain, M., (2013). Biochar Carbon Stability Test Method: An assessment of methods to determine biochar carbon stability. International biochar initiative, 1-10.

Cao, Y., Shen, G., Zhang, Y., Gao, C., Li, Y., Zhang, P., Xiao, W.,and Han, L., (2019). Impacts of carbonization temperature on the Pb (II) adsorption by wheat straw-derived biochar and related mechanism. Science of the Total Environment, 692, 479-489.

Cen, Z. (2021). Develop Biochar-Based Controlled Release Nitrogen Fertilizers (Doctoral dissertation, South Dakota State University).

Cen, Z., Wei, L., Muthukumarappan, K., Sobhan, A., and McDaniel, R. (2021). Assessment of a Biochar-Based Controlled Release Nitrogen Fertilizer Coated with Polylactic Acid. Journal of Soil Science and Plant Nutrition, 1-13.

Chaturvedi, P., Shukla, P., Giri, B.S., Chowdhary, P., Chandra, R., Gupta, P. and Pandey, A. (2021). Prevalence and hazardous impact of pharmaceutical and personal care products and antibiotics in environment: A review on emerging contaminants. Environmental Research, 110664.

Chen, D., Wang, C., Shen, J. Li, Y., and Wu, J. (2018) Response of CH_4 emissions to straw and biochar applications in double-rice cropping systems: Insights from observations and modeling. Environmental Pollution. 235, 95–103.

Chen, L., Chen, X. L., Zhou, C. H., Yang, H. M., Ji, S. F., Tong, D. S.,and Chu, M. Q. (2017). Environmental-friendly montmorillonite-biochar composites: Facile production and tunable adsorption-release of ammonium and phosphate. Journal of cleaner production, 156, 648-659.

Chen, S. S., Maneerung, T., Tsang, D. C., Ok, Y. S., and Wang, C. H. (2017). Valorization of biomass to hydroxymethylfurfural, levulinic acid, and fatty acid methyl ester by heterogeneous catalysts. Chemical Engineering Journal, 328, 246-273.

Chen, X., Dai, Y., Fan, J., Xu, X., and Cao, X. (2020). Application of iron-biochar composite in top soil for simultaneous remediation of chromium-contaminated soil and groundwater: Immobilization mechanism and long-term stability. Journal of Hazardous Materials, 405, 124226.

Chen, S. S., Tsang, D. C., He, M., Sun, Y., Lau, L. S., Leung, R. W., Lau, E.S., Hou, D., Liu, A. and Mohanty, S. (2021). Designing sustainable drainage systems in subtropical cities: Challenges and opportunities. Journal of Cleaner Production, 280, 124418.

Cheng, B. H., Zeng, R. J., and Jiang, H. (2017). Recent developments of post-modification of biochar for electrochemical energy storage. Bioresource technology, 246, 224-233.

Cho, E. J., Kang, J. K., Moon, J. K., Um, B. H., Lee, C. G., Jeong, S., and Park, S. J. (2021). Removal of triclosan from aqueous solution via adsorption by kenaf-derived biochar: its adsorption mechanism study via spectroscopic and experimental approaches. Journal of Environmental Chemical Engineering, 106343.

Chowdhary, P., Gupta, A., Gnansounou, E., Pandey, A., and Chaturvedi, P. (2021). Current trends and possibilities for exploitation of Grape pomace as a potential source for value addition. Environmental Pollution, 278, 116796.

Chung, W.J., Chang, S.W., Chaudhary, D.K., Du Shin, J., Kim, H., Karmegam, N., Govarthanan, M., Chandrasekaran, M., and Ravindran, B. (2021). Effect of biochar amendment on compost quality, gaseous emissions and pathogen reduction during in-vessel composting of chicken manure. Chemosphere.131129.

Cooper, J. A., and McCullough, B. P. (2021). Bracketing sustainability: carbon footprinting March Madness to rethink sustainable tourism approaches and measurements. Journal of Cleaner Production, 318, 128475.

Czech, B., Kończak, M., Rakowska, M., and Oleszczuk, P. (2021). Engineered biochars from organic wastes for the adsorption of diclofenac, naproxen and triclosan from water systems. Journal of Cleaner Production, 288, 125686.

Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P. C., and Xu, J. (2017). Potential role of biochars in decreasing soil acidification-a critical review. Science of the Total Environment, 581, 601-611.

Das, S. K., Ghosh, G. K., Avasthe, R. K., and Sinha, K. (2021). Compositional heterogeneity of different biochar: Effect of pyrolysis temperature and feedstocks. Journal of Environmental Management, 278, 111501.

Deal, C., Brewer, C. E., Brown, R.C., Okure, M.A.E., and Amoding, A. (2012). Comparison of kiln-derived and gasifier-derived biochars as soil amendment in the humid tropics. Biomass Bioenergy. 37:161-8.

Deng, Y., Zhang, T., and Wang, Q. (2017). Biochar adsorption treatment for typical pollutants removal in livestock wastewater: a review. In: Huang, W.-J. (ed.) Engineering applications of biochar. London, UK: IntechOpen.

Desa, U. N. (2016). Transforming our world: The 2030 agenda for sustainable development.

Dhamodharan, K., Ahlawat, S., Kaushal, M., and Rajendran, K. (2020). Economics and cost analysis of waste biorefineries. In Refining Biomass Residues for Sustainable Energy and Bioproducts, Academic Press, 545-565.

Dharmakeerthi, R. S., Hanley, K., Whitman, T., Woolf, D., and Lehmann, J. (2015). Organic carbon dynamics in soils with pyrogenic organic matter that received plant residue additions over seven years. Soil Biology and Biochemistry, 88, 268-274.

Domingues, R.R., Trugilho, P.F., Silva, C.A., De, Melo, ICNA., Melo, L.C.A., Magriotis, Z.M., and Sánchez-Monedero, M.A. (2017). Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits. PLoS One, 12(5):1–19.

Do Minh, T., Song, J., Deb, A., Cha, L., Srivastava, V., and Sillanpää, M. (2020). Biochar based catalysts for the abatement of emerging pollutants: a review. Chemical Engineering Journal, 394, 124856.

Fawzy, S., Osman, A. I., Yang, H., Doran, J., and Rooney, D. W. (2021). Industrial biochar systems for atmospheric carbon removal: a review. Environmental Chemistry Letters, 1-33.

Feng, F., Chen, X., Wang, Q., Xu, W., Long, L., Nabil El-Masry, G., Wan, Q., Yan, H., Cheng, J., and Yu, X. (2020). Use of Bacillus-siamensis-inoculated biochar to decrease uptake of dibutyl phthalate in leafy vegetables. Journal of Environmental Management, 253, 1–8. https://doi.org/10.1016/j.jenvm an.2019.109636

Feng, Y., Xu, Y., Yu, Y., Xie, Z., and Lin, X. (2012). Mechanisms of biochar decreasing methane emission from Chinese paddy soils. Soil Biology and Biochemistry, 46, 80–88.

Fidel, R. B., Laird D. A., and Thompson, M. L. (2017). Characterization and quantification of biochar alkalinity. Chemosphere, 167, 367–373.

Ganguly, P., Sarkhel, R., and Das, P. (2020). Synthesis of pyrolyzed biochar and its application for dye removal: Batch, kinetic and isotherm with linear and non-linear mathematical analysis. Surfaces and Interfaces, 20, 100616.

Gao, X., Peng, Y., Guo, L., Wang, Q., Guan, C. Y., Yang, F., and Chen, Q. (2020). Arsenic adsorption on layered double hydroxides biochars and their amended red and calcareous soils. Journal of Environmental Management, 271, 111045.

Gao, X., Peng, Y., Zhou, Y., Adeel, M., and Chen, Q. (2019). Effects of magnesium ferrite biochar on the cadmium passivation in acidic soil and bioavailability for packoi (Brassica chinensis L.). Journal of Environmental Management, 251, 109610. https://doi.org/10.1016/j.jenvm an.2019.109610

Gąsior, D., and Tic, W. J. (2017). Application of the biochar-based technologies as the way of realization of the sustainable development strategy. Economic and Environmental Studies, 17, 597-611.

Genovese, M., and Lian, K. (2017). Polyoxometalate modified pine cone biochar carbon for supercapacitor electrodes. Journal of Materials Chemistry A, 5, 3939-3947.

González, M. E., Cea, M., Medina, J., González, A., Diez, M. C., Cartes, P., Monreal, C., and Navia, R. (2015). Evaluation of biodegradable polymers as encapsulating agents for the development of a urea controlled-release fertilizer using biochar as support material. Science of the Total Environment, 505, 446-453.

Gray, M., Johnson, M. G., Dragila, M. I., and Kleber, M. (2014). Water uptake in biochars: The roles of porosity and hydrophobicity. Biomass Bioenergy, 61, 196-205.

Gupta, N., Yadav, K. K., Kumar, V., Kumar, S., Chadd, R. P., and Kumar, A. (2019). Trace elements in soil-vegetables interface: Translocation, bioaccumulation, toxicity and amelioration - A review. Science of The Total Environment, 651, 2927–2942.

Gwenzi, W., Chaukura, N., Mukome, F. N. D., Machado, S., and Nyamasoka, B. (2015). Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. Journal of Environmental Management, 150, 250-261.

Hale, S. E., Lehmann, J., Rutherford, D., Zimmerman, A. R., Bachmann, R. T., Shitumbanuma, V., O'Toole, A., Sundqvist, K.L., Arp, H.P.H., and Cornelissen, G. (2012). Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars. Environmental science and technology, 46(5), 2830-2838.

Hamid, Y., Tang, L., Hussain, B., Usman, M., Gurajala, H. K., Rashid, M. S., He, Z., and Yang, X. (2020). Efficiency of lime, biochar, Fe containing biochar and composite amendments for Cd and Pb immobilization in a co-contaminated alluvial soil. Environmental Pollution, 257, 113609.

Hansson, A., Haikola, S., Fridahl, M., Yanda, P., Mabhuye, E., and Pauline, N. (2021). Biochar as multi-purpose sustainable technology: experiences from projects in Tanzania. Environment, Development and Sustainability, 23(4), 5182-5214.

He, M., Xu, Z., Sun, Y., Chan, P.S., Lui, I. and Tsang, D.C. (2021). Critical impacts of pyrolysis conditions and activation methods on application-oriented production of wood waste-derived biochar. Bioresource Technology, 341, 125811.

He, M., Xiong, X., Wang, L., Hou, D., Bolan, N.S., Ok, Y.S., Rinklebe, J. and Tsang, D.C. (2021). A critical review on performance indicators for evaluating soil biota and soil health of biochar-amended soils. Journal of hazardous materials, 125378.

Hou, D., O'Connor, D., Igalavithana, A. D., Alessi, D. S., Luo, J., Tsang, D. C. W., Sparks, D. L., Yamauchi, Y., Rinklebe, J., and Ok, Y. S. (2020). Metal contamination and bioremediation of agricultural soils for food safety and sustainability. Nature Reviews Earth and Environment, 1, 366–381.

Hu, P., Zhang, Y., Liu, L., Wang, X., Luan, X., Ma, X., Chu, P. K., Zhou, J., and Zhao, P. (2019). Biochar/struvite composite as a novel potential material for slow release of N and P. Environmental Science and Pollution Research, 26, 17152–17162.

Hua, B., Li, Z., Gao, W., Feng, H., Chen, N., Li, J., Ji, X., Zhang, L., Wu, Z., Yan, S. and Ren, T., (2021). Soil amendment in plastic greenhouse using modified biochar: soil bacterial diversity responses and microbial biomass carbon and nitrogen. Biotechnology Letters, 43(3), 655-666.

Huang, Q.A., Haruta, A., Kumamoto, Y., Murayama, H., Yamamoto, E., Honma, T., Okumura, M., Nobutou, H. and Tokunaga, M., (2021). Pt/CeO2 with residual chloride as reusable soft Lewis acid catalysts: Application to highly efficient isomerization of allylic esters. Applied Catalysis B: Environmental, 296, 120333.

Huang, Z., Wang, T., Shen, M., Huang, Z., Chong, Y., and Cui, L., (2019). Coagulation treatment of swine wastewater by the method of in-situ forming layered double hydroxides and sludge recycling for preparation of biochar composite catalyst. Chemical Engineering Journal, 369, 784–792

IBI (2013). International Biochar Initiative - IBI. Frequently asked questions about Biochar International Biochar Initiative [internet]. Available at: http://www.biocharinternational.org/biochar/faqs

IBI (2014). International Biochar Initiative - IBI. Standardized product definition and product testing guidelines for biochar that is used in soil [internet]. Ithaca: [s.n.]. Available at: http://www.biocharinternational.org/sites/default/files/IBI_Biochar_Standards_V20_final_2014.pdf

Ilyas, T., Chowdhary, P., Chaurasia, D., Gnansounou, E., Pandey, A., and Chaturvedi, P. (2021). Sustainable green processing of grape pomace for the production of value-added products: An overview. Environmental Technology and Innovation, 101592.

Inyang, M., Gao, B., Zimmerman, A., Zhang, M., and Chen, H. (2014). Synthesis, characterization, and dye sorption ability of carbon nanotube-biochar nanocomposites. Chemical Engineering Journal, 236, 39–46. https://doi.org/10.1016/j.cej.2013.09.074

Jechan, L., Ki-Hyun, K., Eilhann, K. (2017). Biochar as a catalyst. Renewable and Sustainable Energy Reviews, 77, 70–79.

Jindo, K., Mizumoto, H., Sawada, Y., Sanchez-Monedero, M., Sonoki, T. (2014). Physical and chemical characterization of biochars derived from different agricultural residues. Biogeosciences, 11, 6613–6662.

Joseph, S., Graber, E.R., Chia, C., Munroe, P. (2013). Shifting paradigms: development of high-efficiency biochar fertilizers based on nano-structures and soluble components. Carbon Management, 4 (3), 323–343.

Kammann, C., Ippolito, J., Hagemann, N., Borchard, N., Cayuela, M. L., Estavillo, J. M., and Wrage-Mönnig, N. (2017). Biochar as a tool to reduce the agricultural greenhouse-gas burden–knowns, unknowns and future research needs. Journal of Environmental Engineering and Landscape Management, 25(2), 114-139.

Keerthanan, S., Bhatnagar, A., Mahatantila, K., Jayasinghe, C., Ok, Y.S. and Vithanage, M. (2020). Engineered tea-waste biochar for the removal of caffeine, a model compound in pharmaceuticals and personal care products (PPCPs), from aqueous media. Environmental Technology and Innovation, 19, 100847.

Keerthanan, S., Rajapaksha, S. M., Trakal, L., and Vithanage, M. (2020). Caffeine removal by Gliricidiasepium biochar: Influence of pyrolysis temperature and physicochemical properties. Environmental Research, 189, 109865.

Khadem, A., Raiesi, F., Besharati, H., and Khalaj, M. A. (2021). The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. Biochar, 3(1), 105-116.

Khan, N., Chowdhary, P., Ahmad, A., Giri, B. S., and Chaturvedi, P. (2020). Hydrothermal liquefaction of rice husk and cow dung in Mixed-Bed-Rotating Pyrolyzer and application of biochar for dye removal. Bioresource technology, 309, 123294.

Khan, N., Chowdhary, P., Gnansounou, E., and Chaturvedi, P. (2021). Biochar and environmental sustainability: Emerging trends and techno-economic perspectives. Bioresource Technology, 125102.

Kim, K. H., Kim, J. Y., Cho, T. S., and Choi, J. W. (2012). Influence of pyrolysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (Pinus rigida). Bioresource technology, 118, 158-162.

Kong, X., Liu, Y., Pi, J., Li, W., Liao, Q., and Shang, J. (2017). Low-cost magnetic herbal biochar: characterization and application for antibiotic removal. Environmental Science and Pollution Research, 24(7), 6679-6687.

Kookana, R. S., Sarmah, A. K., Van Zwieten, L., Krull, E., and Singh, B. (2011). Biochar application to soil: agronomic and environmental benefits and unintended consequences. Advances in agronomy, 112, 103-143.

Kour, D., Rana, K. L., Yadav, N., Yadav, A. N., Rastegari, A. A., Singh, C., Negi, P., Singh, K., and Saxena, A. K. (2019). Technologies for biofuel production: current development, challenges, and future prospects. In Prospects of renewable bioprocessing in future energy systems, Springer, Cham, 1-50.

Kumar, M., Bolan, N. S., Hoang, S. A., Sawarkar, A. D., Jasemizad, T., Gao, B., and Rinklebe, J. (2021). Remediation of soils and sediments polluted with polycyclic aromatic hydrocarbons: To immobilize, mobilize, or degrade?. Journal of Hazardous Materials, 420, 126534.

Lee, J., Jung, J. M., Oh, J. I., Ok, Y. S., Lee, S. R., and Kwon, E. E. (2017a). Evaluating the effectiveness of various biochars as porous media for biodiesel synthesis via pseudo-catalytic transesterification. Bioresource technology, 231, 59-64.

Lee, J., Kim, K. H., and Kwon, E. E. (2017b). Biochar as a catalyst. Renewable and Sustainable Energy Reviews, 77, 70-79.

Li, C., Hayashi, J. I., Sun, Y., Zhang, L., Zhang, S., Wang, S., and Hu, X. (2021). Impact of heating rates on the evolution of function groups of the biochar from lignin pyrolysis. Journal of Analytical and Applied Pyrolysis, 155, 105031.

Li, J., Li, Y., Wu, Y., and Zheng, M. (2014). A comparison of biochars from lignin, cellulose and wood as the sorbent to an aromatic pollutant. Journal of hazardous materials, 280, 450-457.

Li, L., Zhang, Y. J., Novak, A., Yang, Y., and Wang, J. (2021). Role of Biochar in Improving Sandy Soil Water Retention and Resilience to Drought. Water, 13(4), 407.

Li, R., Deng, H., Zhang, X., Wang, J.J., Awasthi, M.K., Wang, Q., Xiao, R., Zhou, B., Du, J., and Zhang, Z. (2019). High-efficiency removal of Pb (II) and humate by a CeO2–MoS2 hybrid magnetic biochar. Bioresource technology, 273, 335-340.

Li, R., Wang, J. J., Zhang, Z., Awasthi, M. K., Du, D., Dang, P., Huang, Q., Zhang, Y., and Wang, L., (2018a). Recovery of phosphate and dissolved organic matter from aqueous solution using a novel CaO-MgO hybrid carbon composite and its feasibility in phosphorus recycling. Science of the Total Environment, 642, 526–536.

Li, R., Wang, Z., Zhao, X., Li, X., and Xie, X. (2018). Magnetic biochar-based manganese oxide composite for enhanced fluoroquinolone antibiotic removal from water. Environmental Science and Pollution Research, 25(31), 31136-31148.

Li, S., Barreto, V., Li, R., Chen, G., and Hsieh, Y.P., (2018b). Nitrogen retention of biochar derived from different feedstocks at variable pyrolysis temperatures, Journal of Analytical and Applied Pyrolysis, 133, 136-146.

Li, X., Wang, C., Zhang, J., Liu, J., Liu, B., and Chen, G. (2020). Preparation and application of magnetic biochar in water treatment: A critical review. Science of The Total Environment, 711, 134847.https://doi.org/10.1016/j.scitotenv.2019.134847

Liu, L., Zhao, J., Liu, X., Bai, S., Lin, H. and Wang, D., (2021). Reduction and removal of As (V) in aqueous solution by biochar derived from nano zero-valent-iron (nZVI) and sewage sludge. Chemosphere, 277, p.130273.

Liu, S., Kong, F., Li, Y., Jiang, Z., Xi, M., and Wu, J. (2020). Mineral-ions modified biochars enhance the stability of soil aggregate and soil carbon sequestration in a coastal wetland soil. Catena, 193, 104618.

Liu, S., Meng, J., Jiang, L., Yang, X., Lan, Y., Cheng, X., and Chen, W. (2017). Rice husk biochar impacts soil phosphorous availability, phosphatase activities and bacterial community characteristics in three different soil types. Applied Soil Ecology, 116, 12-22.

Liu, Y., He, P., Shao, L., Zhang, H., and Lü, F. (2017). Significant enhancement by biochar of caproate production via chain elongation. Water research, 119, 150-159.

Liu, Y., Yang, M., Wu, Y., Wang, H., Chen, Y., and Wu, W. (2011). Reducing CH_4 and CO_2 emissions from waterlogged paddy soil with biochar. Journal of Soils and Sediments, 11(6), 930-939.

Lu, F., Wang, C., Chen, M., Yue, F., and Ralph, J. (2021). A facile spectroscopic method for measuring lignin content in lignocellulosic biomass. Green Chemistry.

Luo, K., Pang, Y., Wang, D., Li, X., Wang, L., Lei, M., Huang, Q., and Yang, Q. (2021). A critical review on the application of biochar in environmental pollution remediation: Role of persistent free radicals (PFRs). Journal of Environmental Sciences, 108, 201-216.

Lyu, H., Tang, J., Cui, M., Gao, B., and Shen, B. (2020). Biochar/iron (BC/Fe) composites for soil and groundwater remediation: Synthesis, applications, and mechanisms. Chemosphere, 246, 125609. https://doi.org/10.1016/j.chemo sphere.2019.125609

Ma, L. J., Wang, Q., Islam, S. M., Liu, Y. C., Ma, S. L., and Kanatzidis, M. G. (2016). Highly selective and efficient removal of heavy metals by layered double hydroxide intercalated with the MoS_4^{2-} ion. Journal of the American Chemical Society, 138, 2858–2866. https://doi.org/10.1021/jacs.6b00110

Manyà, J. J., and Gascó, G. (2021). Biochar as a Sustainable Resource to Drive Innovative Green Technologies. In Biochar as a Renewable-Based Material: With Applications in Agriculture, the Environment and Energy, 1-33.

Mašek, O., Buss, W., Brownsort, P., Rovere, M., Tagliaferro, A., Zhao, L., and Xu, G. (2019). Potassium doping increases biochar carbon sequestration potential by 45%, facilitating decoupling of carbon sequestration from soil improvement. Scientific reports, 9, 1-8

Mašek, O., Buss, W., Brownsort, P., Rovere, M., Tagliaferro, A., Zhao, L., Cao, X. and Xu, G. (2019). Potassium doping increases biochar carbon sequestration potential by 45%, facilitating decoupling of carbon sequestration from soil improvement. Scientific reports, 9(1), 1-8.

Meili, L., Lins, P. V., Zanta, C. L. P. S., Soletti, J. I., Ribeiro, L. M. O., Dornelas, C. B., and Vieira, M. G. A. (2019). MgAl-LDH/Biochar composites for methylene blue removal by adsorption. Applied Clay Science, 168, 11-20.

Mensah, R. A., Shanmugam, V., Narayanan, S., Razavi, S. M. J., Ulfberg, A., Blanksvärd, T., Sayahi, F., Simonsson, P., Reinke, B., Försth, M., Sas, G. and Das, O. (2021). Biochar-Added Cementitious Materials-A Review on Mechanical, Thermal, and Environmental Properties. Sustainability, 13(16), 9336.

Mohamed, B. A., Ellis, N., Kim, C. S., Bi, X., and Chen, W. H. (2021). Engineered biochars from catalytic microwave pyrolysis for reducing heavy metals phytotoxicity and increasing plant growth. Chemosphere, 271, 129808.

Mohan, D., Sarswat, A., Ok, Y. S., and Pittman Jr, C. U. (2014). Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review. Bioresource technology, 160, 191-202.

Mona, S., Malyan, S. K., Saini, N., Deepak, B., Pugazhendhi, A., and Kumar, S. S. (2021). Towards sustainable agriculture with carbon sequestration, and greenhouse gas mitigation using algal biochar. Chemosphere, 129856.

Morales, M. M., Comerford, N. B., Behling, M., de Abreu, D. C., and Guerrini, I. A. (2021). Biochar Chemistry in a Weathered Tropical Soil: Kinetics of Phosphorus Sorption. Agriculture, 11(4), 295.

Mukherjee, A., Zimmerman, A. R., and Harris, W. (2011). Surface chemistry variations among a series of laboratory-produced biochars. Geoderma, 163, 247-255.

Neogi, S., Dash, P. K., Bhattacharyya, P., Padhy, S. R., Roy, K. S., and Nayak, A. K. (2020). Partitioning of total soil respiration into root, rhizosphere and basal-soil CO2 fluxes in contrasting rice production systems. Soil Research, 58, 592-601.

Nguyen, B. T., Trinh, N. N., and Bach, Q. V. (2020). Methane emissions and associated microbial activities from paddy salt-affected soil as influenced by biochar and cow manure addition. Applied Soil Ecology, 152, 103531.

Nguyen, D.L.T., Binh, Q.A., Nguyen, X.C., Nguyen, T.T.H., Vo, Q.N., Nguyen, T.D., Tran, T.C.P., Nguyen, T.A.H., Kim, S.Y., Nguyen, T.P. and Bae, J., (2021). Metal salt-modified biochars derived from agro-waste for effective congo red dye removal. Environmental Research, 111492.

Nwajiaku, I. M., Olanrewaju, J. S., Sato, K., Tokunari, T., Kitano, S., and Masunaga, T. (2018). Change in nutrient composition of biochar from rice husk and sugarcane bagasse at varying pyrolytic temperatures. International Journal of Recycling of Organic Waste in Agriculture, 7, 269-276.

Ojha, D. K., Viju, D., and Vinu, R. (2021). Fast pyrolysis kinetics of lignocellulosic biomass of varying compositions. Energy Conversion and Management: X, 10, 100071.

Palansooriya, K. N., Wong, J. T. F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S. X., Bolan, N., Wang, H., and Ok, Y. S. (2019). Response of microbial communities to biochar-amended soils: a critical review. Biochar, 1(1), 3-22.

Paunovic, O., Pap, S., Maletic, S., Taggart, M. A., Boskovic, N., and Sekulic, M. T. (2019). Ionisable emerging pharmaceutical adsorption onto microwave functionalised biochar derived from novel lignocellulosic waste biomass. Journal of colloid and interface science, 547, 350-360.

Pirbazari, S. M., Norouzi, O., Kohansal, K., and Tavasoli, A. (2019). Experimental studies on high-quality bio-oil production via pyrolysis of Azolla by the use of a three metallic/modified pyrochar catalyst. Bioresource technology, 291, 121802.

Pratiwi, E. P. A., and Shinogi, Y. (2016). Rice husk biochar application to paddy soil and its effects on soil physical properties, plant growth, and methane emission. Paddy and water environment, 14(4), 521-532.

Praveen, S., Gokulan, R., Pushpa, T. B., and Jegan, J. (2021). Techno-economic feasibility of biochar as biosorbent for basic dye sequestration. Journal of the Indian Chemical Society, 98(8), 100107.

Qian, L., Chen, L., Joseph, S., Pan, G., Li, L., Zheng, J., and Wang, J. (2014). Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China. Carbon Management, 5, 145-154.

Rathnayake, D., Ehidiamhen, P. O., Egene, C. E., Stevens, C. V., Meers, E., Mašek, O., and Ronsse, F. (2021). Investigation of biomass and agricultural plastic co-pyrolysis: Effect on biochar yield and properties. Journal of Analytical and Applied Pyrolysis, 155, 105029.

Rehman, A., Arif, M.S., Tufail, M.A., Shahzad, S.M., Farooq, T.H., Ahmed, W., Mehmood, T., Farooq, M.R., Javed, Z. and Shakoor, A., (2021). Biochar potential to relegate metal toxicity effects is more soil driven than plant system: A global meta-analysis. Journal of Cleaner Production, 316, 128276.

Rwiza, M. J., Oh, S. Y., Kim, K. W., and Kim, S. D. (2018). Comparative sorption isotherms and removal studies for Pb (II) by physical and thermochemical modification of low-cost agro-wastes from Tanzania. Chemosphere, 195, 135-145.

Sahoo, K., Bilek, E., Bergman, R., and Mani, S. (2019). Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. Applied Energy, 235, 578-590.

Schmidt, H. P., Hagemann, N., Draper, K., and Kammann, C. (2019). The use of biochar in animal feeding. PeerJ, 7, e7373.

Shalini, S.S., Palanivelu, K., and Ramachandran, A. (2020). Biochar from biomass waste as a renewable carbon material for climate change mitigation in reducing greenhouse gas emissions - a review. Biomass Conversion and Biorefinery, 1-21

Sharma, P., and Melkania, U. (2017). Biochar-enhanced hydrogen production from organic fraction of municipal solid waste using co-culture of Enterobacter aerogenes and E. coli. International Journal of Hydrogen Energy, 42-30, 18865-18874.

Shen, Y., Forrester, S., Koval, J., and Urgun-Demirtas, M. (2017). Yearlong semi-continuous operation of thermophilic two-stage anaerobic digesters amended with biochar for enhanced biomethane production. Journal of Cleaner Production, 167, 863-874

Shen, Y., Linville, J. L., Ignacio-de Leon, P. A. A., Schoene, R. P., and Urgun-Demirtas, M. (2016). Towards a sustainable paradigm of waste-to-energy process: Enhanced anaerobic digestion of sludge with woody biochar. Journal of Cleaner Production, 135, 1054-1064

Shen, Z., Zhang, J., Hou, D., Tsang, D. C. W., Ok, Y. S., and Alessi, D. S. (2019). Synthesis of MgO-coated corncob biochar and its application in lead stabilization in a soil washing residue. Environment International, 122, 357–362. https://doi.org/10.1016/j.envint.2018.11.045

Shen, X., Meng, H., Shen, Y., Ding, J., Zhou, H., Cong, H., and Li, L. (2022). A comprehensive assessment on bioavailability, leaching characteristics and potential risk of polycyclic aromatic hydrocarbons in biochars produced by a continuous pyrolysis system. Chemosphere, 287, 132116.

Shukla, P., Giri, B. S., Mishra, R. K., Pandey, A., and Chaturvedi, P. (2021). Lignocellulosic biomass-based engineered biochar composites: A facile strategy for abatement of emerging pollutants and utilization in industrial applications. Renewable and Sustainable Energy Reviews, 152, 111643

Singh, C., Tiwari, S., and Singh, J. S. (2019). Biochar: a sustainable tool in soil pollutant bioremediation.In: Bharagava RN, Saxena G (eds) Bioremediation of Industrial Waste for Environmental Safety. Singapore, Springer, 475–494

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., and Keesstra, S. (2019). Impacts of Land-Based Greenhouse Gas Removal Options on Ecosystem Services and the United Nations Sustainable Development Goals. Annual Review of Environment and Resources, 44

Son, E.B., Poo, K.M., Chang, J.S., and Chae, K.J. (2018). Heavy metal removal from aqueous solutions using engineered magnetic biochars derived from waste marine macro-algal biomass. Science of The Total Environment, 615, 161–168

Suárez-Hernández, L., Ardila-A, A. N., and Barrera-Zapata, R. (2017). Morphological and physicochemical characterization of biochar produced by gasification of selected forestry species. RevistaFacultad de Ingeniería, 26, 123–130

Sui, Y., Gao, J., Liu, C., Zhang, W., Lan, Y., Li, S., Meng, J., Xu, Z., and Tang, L. (2016). Interactive effects of straw-derived biochar and N fertilization on soil C storage and rice productivity in rice paddies of Northeast China. Science of Total Environment, 544, 203–210

Suliman, W., Harsh, J. B., Abu-Lail, N. I., Fortuna, A. M., Dallmeyer, I., and Garcia-Pérez, M. (2017). The role of biochar porosity and surface functionality in augmenting hydrologic properties of a sandy soil. Science of the Total Environment, 574, 139–147

Sun, D., Meng, J., Liang, H., Yang, E., Huang, Y., Chen, W., Jiang, L., Lan, Y., Zhang, W., and Gao, J. (2015). Effect of volatile organic compounds absorbed to fresh biochar on survival of *Bacillus mucilaginosus* and structure of soil microbial communities. Journal of Soils and Sediments, 15, 271-81

Sun, H., Zhang, H., Min, J., Feng, Y., and Shi, W. (2016). Controlled-release fertilizer, floating duckweed, and biochar affect ammonia volatilization and nitrous oxide emission from rice paddy fields irrigated with nitrogen-rich wastewater. Paddy and water environment, 14, 105–111

Sun, X., Atiyeh, H. K., Adesanya, Y. A., Zhang, H., Okonkwo, C., and Ezeji, T. (2019). Enhanced acetone-butanol-ethanol production by Clostridium beijerinckii using biochar. ASABE Annual International Meeting. American Society of Agricultural and Biological Engineers.

Sun, X., Atiyeh, H. K., Adesanya, Y., Okonkwo, C., Zhang, H., Huhnke, R. L., and Ezeji, T. (2020). Feasibility of using biochar as buffer and mineral nutrients replacement for acetone-butanol-ethanol production from non-detoxified switchgrass hydrolysate. Bioresource technology, 298, 122569.

Sun, X., Atiyeh, H. K., Li, M., and Chen, Y. (2020). Biochar facilitated bioprocessing and biorefinery for productions of biofuel and chemicals: A review. Bioresource technology, 295, 122252

Sun, X., Ding, J., Jiang, Z., and Xu, J. (2019). Biochar improved rice yield and mitigated CH_4 and N_2O emissions from paddy field under controlled irrigation in the Taihu Lake Region of China. Atmospheric Environment, 200, 69–77

Sun, Y., Xiong, X., He, M., Xu, Z., Hou, D., Zhang, W., Ok, Y.S., Rinklebe, J., Wang, L. and Tsang, D.C. (2021). Roles of biochar-derived dissolved organic matter in soil amendment and environmental remediation: A critical review. Chemical Engineering Journal, 130387.

Sunyoto, N. M., Zhu, M., Zhang, Z., and Zhang, D. (2016). Effect of biochar addition on hydrogen and methane production in two-phase anaerobic digestion of aqueous carbohydrates food waste. Bioresource technology, 219, 29-36

Sutradhar, I., Jackson-deGraffenried, M., Akter, S., McMahon, S. A., Waid, J. L., Schmidt, H. P., Wendt, A. S., and Gabrysch, S. (2021). Introducing urine-enriched biochar-based fertilizer for vegetable production: acceptability and results from rural Bangladesh. Environment, Development and Sustainability, 1-22.

Tang, Y., Alam, M.S., Konhauser, K.O., Alessi, D.S., Xu, S., Tian, W., and Liu, Y. (2019). Influence of pyrolysis temperature on production of digested sludge biochar and its application for ammonium removal from municipal wastewater. Science of the Total Environment. 209, 927-936

Tomczyk, A., Sokołowska, Z., and Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Bio/Technology, 19(1), 191-215.

Trinh, M.V., Tesfai, M., Borrell, A., Nagothu, U.S., Bui, T.P.L., Quynh, V.D., and Thanh, L.Q. (2017). Effect of organic, inorganic and slow-release urea fertilisers on CH4 and N2O emissions from rice paddy fields. Paddy Water Environment, 15, 317-330.

Tu, C., Wei, J., Guan, F., Liu, Y., Sun, Y., and Luo, Y. (2020). Biochar and bacteria inoculated biochar enhanced Cd and Cu immobilization and enzymatic activity in a polluted soil. Environment International, 137, 105576. https://doi.org/10.1016/j.envint.2020.105576

UN. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. UN.

von Gunten, K., Alam, M. S., Hubmann, M., Ok, Y. S., Konhauser, K. O., and Alessi, D. S. (2017). Modified sequential extraction for biochar and petroleum coke: Metal release potential and its environmental implications. Bioresource technology, 236, 106-110.

Vyavahare, G. D., Gurav, R. G., Jadhav, P. P., Patil, R. R., Aware, C. B., and Jadhav, J. P. (2018). Response surface methodology optimization for sorption of malachite green dye on sugarcane bagasse biochar and evaluating the residual dye for phyto and cytogenotoxicity. Chemosphere, 194, 306-315

Wan, S., Wang, S., Li, Y., and Gao, B. (2017). Functionalizing biochar with Mg–Al and Mg–Fe layered double hydroxides for removal of phosphate from aqueous solutions. Journal of Industrial and Engineering Chemistry, 47, 246–253. https://doi.org/10.1016/j.jiec.2016.11.039

Wang, B., Wang, Z., Jiang, Y., Tan, G., Xu, N., and Xu, Y. (2017). Enhanced power generation and wastewater treatment in sustainable biochar electrodes based bioelectrochemical system. Bioresource Technology. 241, 841-848.

Wang, C., Lu, H., Dong, D., Deng, H., Strong, P.J., Wang, H., and Wu, W. (2013). Insight into the effects of biochar on manure composting: Evidence supporting the relationship between N_2O emission and denitrifying community. Environmental Science and Technology. 47, 7341-7349.

Wang, C.T., Sangeetha, T., Ding, D.Q., Chong, W.T., and Yan, W.M. (2018). Implementation of surface modified carbon cloth electrodes with biochar particles in microbial fuel cells. International Journal of Green Energy. 15(13), 789-794.

Wang, L., O'Connor, D., Rinklebe, J., Ok, Y.S., Tsang, D.C.W., Shen, Z., and Hou, D. (2020). Biochar aging: Mechanisms, physicochemical changes, assessment, and implications for field applications. Environmental Science and Technology. 54, 14797-14814.

Wang, L., Ok Y.S., Tsang D.C.W., Alessi D.S., Rinklebe J., Mašek O., Bolan N.S., and Hou D. (2021). Biochar composites: Emerging trends, field successes and sustainability implications. Soil Use and Management. https://doi.org/10.1111/sum.12731

Weber, K., and Quicker, P. (2018). Properties of biochar. Fuel 217, 240-261.

Wei, J., Liu, Y., Li, J., Zhu, Y., Yu, H., and Peng, Y. (2019). Adsorption and co-adsorption of tetracycline and doxycycline by one-step synthesized iron loaded sludge biochar. Chemosphere, 236, 124254.

Wei, M., Liu, X., He, Y., Xu, X., Wu, Z., Yu, K., and Zheng, X. (2020). Biochar inoculated with *Pseudomonas putida* improves grape (*Vitis vinifera L.*) fruit quality and alters bacterial diversity. Rhizosphere, 16, 100261. https://doi.org/10.1016/j.rhisph.2020.100261

Wen, P., Wu, Z.S., Han, Y.J., Cravotto, G., Wang, J., and Ye, B.C. (2017). Microwave-assisted synthesis of a novel biochar-based slow-release nitrogen fertilizer with enhanced water-retention capacity. ACS Sustainable Chemistry and Engineering. 5 (8), 7374-7382.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., and Joseph, S. (2010). Sustainable biochar to mitigate global climate change. Nature communications. 1(1), 1-9.

Wu, H., Qin, X., Wu, H., Li, F., Wu, J., Zheng, L., Wang, J., Chen, J., Zhao, Y., Lin, S. and Lin, W. (2020). Biochar mediates microbial communities and their metabolic characteristics under continuous monoculture. Chemosphere. 246. 125835.

Wu, J., Dong, L., Zhou, C., Liu, B., Xing, D., Feng, L., and Cao, G. (2019). Enhanced butanol-hydrogen coproduction by Clostridium beijerinckii with biochar as cell's carrier. Bioresource Technology. 294, 122141.

Xia, H., Riaz, M., Zhang, M., Liu, B., Li, Y., El-Desouki, Z. and Jiang, C. (2022). Biochar-N fertilizer interaction increases N utilization efficiency by modifying soil C/N component under N fertilizer deep placement modes. Chemosphere. 286. 131594.

Xiang, Y., Xu, Z., Zhou, Y., Wei, Y., Long, X., He, Y., Zhi, D., Yang, J. and Luo, L. (2019). A sustainable ferromanganese biochar adsorbent for effective levofloxacin removal from aqueous medium. Chemosphere. 237, 124464.

Xiao, F., Cheng, J., Cao, W., Yang, C., Chen, J., and Luo, Z. (2019). Removal of heavy metals from aqueous solution using chitosan-combined magnetic biochars. Journal of colloid and interface science. 540, 579-584

Xie, T., Reddy, K.R., Wang, C., Yargicoglu, E., and Spokas, K. (2015). Characteristics and applications of biochar for environmental remediation: a review. Critical Reviews in Environmental Science and Technology. 45(9), 939-969.

Xiong, B., Zhang, Y., Hou, Y., Arp, H. P. H., Reid, B. J., and Cai, C. (2017). Enhanced biodegradation of PAHs in historically contaminated soil by M. gilvum inoculated biochar. Chemosphere, 182, 316–324. https://doi.org/10.1016/j.chemo sphere.2017.05.020

Xu, X., Cheng, K., Wu, H., Sun, J., Yue, Q., and Pan, G. (2019). Greenhouse gas mitigation potential in crop production with biochar soil amendment—a carbon footprint assessment for cross-site field experiments from China. Gcb Bioenergy, 11(4), 592-605.

Yaashikaa, P.R., Kumar, P.S., Varjani, S.J., and Saravanan, A. (2019). Advances in production and application of biochar from lignocellulosic feedstocks for remediation of environmental pollutants. Bioresource Technology. 292, 122030.

Yaashikaa, P. R., Kumar, P. S., Varjani, S., and Saravanan, A. (2020). A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. Biotechnology Reports, e00570.

Yanala, S. R., and Pagilla, K. R. (2020). Use of biochar to produce reclaimed water for irrigation use. Chemosphere, 251, 126403.

Yang, F., Xu, Z., Huang, Y., Tsang, D.C., Ok, Y.S., Zhao, L., Qiu, H., Xu, X. and Cao, X. (2021). Stabilization of dissolvable biochar by soil minerals: Release reduction and organo-mineral complexes formation. Journal of hazardous materials, 412, 125213.

Yang, S., Jiang, Z., Sun, X., Ding, J., and Xu, J. (2018). Effects of biochar amendment on CO_2 emissions from paddy fields under water-saving irrigation. International Journal of Environmental Research and Public Health. 15, 2580.

Yang, X., Zhang, S., Ju, M., and Liu, L. (2019). Preparation and modification of biochar materials and their application in soil remediation. Applied Sciences. 9(7), 1365.

Yang, Y., Ok, Y. S., Kim, K. H., Kwon, E. E., and Tsang, Y. F. (2017). Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: A review. Science of the Total Environment, 596, 303-320.

Yao, X., Ji, L., Guo, J., Ge, S., Lu, W., Cai, L., Wang, Y., Song, W. and Zhang, H., (2020). Magnetic activated biochar nanocomposites derived from wakame and its application in methylene blue adsorption. Bioresource technology, 302, 122842.

Yin, X., Peñuelas, J., Sardans, J., Xu, X., Chen, Y., Fang, Y., Wu, L., Singh, B.P., Tavakkoli, E. and Wang, W. (2021). Effects of nitrogen-enriched biochar on rice growth and yield, iron dynamics, and soil carbon storage and emissions: A tool to improve sustainable rice cultivation. Environmental Pollution, 117565.

Yu, X., Liu, Y., Wang, Y., Feng, X., Tu, M., and Chen, J. (2020). Role of bioengineering and laborers in integration of farmland resources toward to improve dimension of sustainable agriculture in China. Bioengineered, 11(1), 559-571.

Yu, J., Zhu, Z., Zhang, H., Qiu, Y. and Yin, D., (2018). Mg-Fe layered double hydroxide assembled on biochar derived from rice husk ash: facile synthesis and application in efficient removal of heavy metals. Environmental science and pollution research. 25(24), 24293-24304.

Yumin, D., Mehariya, S., Kumar, A., Singh, E., Yang, Jianfeng., Kumar, S., Li, H., and Awasthi, M.K. (2021). Apple orchard waste recycling and valorization of valuable product-A review. Bioengineered. 12(1), 476-495.

Zhang, H., Voroney, R.P., and Price, G.W., (2015). Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. Soil Biology and Biochemistry. 83, 19-28.

Zhang, J., Fan, C., and Zang, L. (2017). Improvement of hydrogen production from glucose by ferrous iron and biochar. Bioresource technology, 245, 98-105.

Zhang, J., Huang, B., Chen, L., Li, Y., Li, W., and Luo, Z. (2018). Characteristics of biochar produced from yak manure at different pyrolysis temperatures and its effects on the yield and growth of highland barley. chemical speciation and bioavailability 30(1), 57-67.

Zhang, P., O'Connor, D., Wang, Y., Jiang, L., Xia, T., Wang, L., Tsang, D.C., Ok, Y.S. and Hou, D., (2020). A green biochar/iron oxide composite for methylene blue removal. Journal of hazardous materials, 384, p.121286.

Zhao, C., Lv, P., Yang, L., Xing, S., Luo, W., and Wang, Z. (2018). Biodiesel synthesis over biochar-based catalyst from biomass waste pomelo peel. Energy Conversion and Management. 160, 477-485.

Zhou, D., Liu, D., Gao, F., Li, M., and Luo, X., (2017). Effects of biochar-derived sewage sludge on heavy metal adsorption and immobilization in soils. International Journal of Environmental Research and Public Health. 14, 681

Zhou, Z., Liu, Y.G., Liu, S.B., Liu, H.Y., Zeng, G.M., Tan, X.F., Yang, C.P., Ding, Y., Yan, Z.L. and Cai, X.X., (2017). Sorption performance and mechanisms of arsenic (V) removal by magnetic gelatin-modified biochar. Chemical Engineering Journal, 314, 223-231.

Zhu, X., He, M., Sun, Y., Xu, Z., Wan, Z., Hou, D., Alessi, D.S. and Tsang, D.C. (2022). Insights into the adsorption of pharmaceuticals and personal care products (PPCPs) on biochar and activated carbon with the aid of machine learning. Journal of Hazardous Materials, 423,127060.

Zimmerman, A.R. (2010). Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). Environmental Science and Technology. 44, 1295-1301.