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Assessing the potential sustainability benefit of Agricultural residues: Biomass conversion to Biochar and its use for soil and crop improvement

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AGRICULTURAL residues represent a significant challenge to proper management. Biochar provides a sustainable way for the management of agricultural residue and other waste biomass. Biochar is a form of carbonized biomass which have received attention due to its wide application. Pyrolysis, torrefaction, gasification, hydrothermal carbonization, and standard carbonization techniques are used for biochar preparation. Properties of biochar depends on the techniques and environment used to produce it. In order to optimise the performance of biochar for particular purposes, physical, chemical and biological modification has been opted by different researchers. Direct application of biochar in the agricultural soil reported to improve the soil pH, water holding capacity, fertility, crop growth and yield. Biochar also act as slow release fertilizers (SRFs), which have a huge potential to increase the soil fertility along with agronomic performance and decrease the amount of greenhouse gases released into the environment from the soil. Overall, use of biochar as sustainable high-value products seems to have a very promising future. This review provides a comprehensive review of the material and methods for biochar preparation, modification techniques, properties of biochar and its performance in agriculture soil.

Keywords: Agriculture waste: Biochar: Pyrolysis: Organic matter: Soil remediation.

1. Introduction

Food security is one of the biggest challenges globally due to rapid increase in population. Decreasing agricultural land and agricultural productivity affects millions of people thereby resulting in malnutrition and poverty (Steensland, 2021). The pressure for the fulfillment of food security falls on the remaining portion of the agricultural land. Farmers are trying to get maximum production from small agricultural lands, resulting into using different chemical fertilizers. Improper and excessive use of these fertiliers causes their accumulation in soil which leads to soil degradation (Pahalvi et al., 2021). It is estimated that 30% of soil worldwide is currently degraded (Nascimento et al., 2021).

As, another big problem the present civilization faces is improper waste management which results in water and soil pollution and is a cause of greenhouse emissions (Xiao et al., 2021). Therefore, it seems justified to seek solutions for food production based on natural nutrient cycling, with the simultaneous use of agricultural waste as fertilizers. One possibility of recovering nutrients from waste and reusing them to improve soil efficiency is biochar (BC) production. In the last few years, the usage of biochar applications has gotten a good focus and the number of publications in this field have increased too.

Biochar is a type of charcoal which is used as a soil conditioner to help plants grow, for agricultural purposes and for carbon capture and storage, as opposed to conventional charcoal, which is commonly used as a fuel (Muhammad et al., 2020). Due to the local availability of the biochar raw material and the option of availability of easy synthesis techniques and application steps, biochar can be one of the best choices for soil remediation techniques. In order to optimise the performance of biochar for particular purposes, numerous techniques have been investigated, evaluated, and devised to modify and adjust its properties. The application of biochar alters the soil pH, water holding capacity, fertility and also stimulates a heterogeneous response in microbial species.

Although review papers related to production, characterization, properties and applications of BC and B-SRF in agriculture soil are available. A comprehensive review regarding the specific production of biochar from agricultural residue itself, modification of biochar for application in agricultural soil as direct biochar and slow release fertilizer is still lacking. This review offers an in-depth understanding of biochar application in agriculture.

2. **Agricultural residue derived Biochar**

Biochar production from waste biomass is an economical and beneficial alternative to fossil fuels,

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providing clean alternatives and mitigating climate change (Shalini et al., 2021). The process of breaking down biomass into charcoal, oil, and gaseous substances can be accomplished through many ways such as pyrolysis (slow/fast/flash), torrefaction, gasification, hydrothermal carbonization (HTC), & standard carbonization techniques. Agro residue includes Rice and wheat straw (Bhatnagar et al., 2022), corn stover (Gong et al., 2021), Canola straw biochar (Kwak et al., 2019), corncob, coconut husk, coconut shell (Khawkomol et al., 2021), sugarcane bagasse (Miranda et al., 2021), peanut shells (Kushwaha et al., 2023), and many more materials have been studied (Fig 1a). The journal Science of Total Environment exhibited the greatest quantity of publications, with China being the country with the highest publication volume (Fig 1b). Fig. 1c, demonstrates a bibliometric analysis of publications to date in Scopus that contain the keyword "biochar" in conjunction with different agro-residues individually: wheat bran, husk, straw; rice husk, straw; cotton stalk; sugarcane bagasse; corn cob, stover; chaff. This demonstrated that rice straw is the agro-residue most frequently utilised in environmental science research for biochar production.

3. **Biochar Preparation**

BC can have varying properties depending on the technology used to produce it e.g., Pyrolysis, torrefaction, slow pyrolysis, intermediate pyrolysis, etc. As shown through Fig.2, researchers has used pyrolysis techniques more frequently for the biochar preparation. Pyrolysis can be performed in reactors with continuous and batch modes. Continuous mode often results in high operational efficiency and higher biochar yields compared to batch mode (Ge et al., 2021). Microwave-assisted pyrolysis has gained attention as a promising alternative to standard pyrolysis ways due to its uniform, selective, and volumetric heating, enhanced energy efficiency, and rapid heating rate (Sakhiya et al., 2020; Chen et al., 2022). Slow pyrolysis is a continuous process in which purged (oxygen free) feedstock biomass is transferred into an external heated furnace; "fast" pyrolysis, on the other hand, is based on very rapid heat transfer, typically to fine biomass particles at less than 650 C with rapid heating rate (100-1000° C/s) (Fahmy et al., 2020; Tan et al., 2021; Shen et al., 2023). The bibliometric analysis of publications in Scopus using keywords (Biochar AND preparation AND Pyrolysis/ microwave pyrolysis/ co-pyrolysis/ thermal/ hydrothermal/ slow/ intermediate/ gasification/ torrefaction/ combustion) was done which revealed that biochar preparation by pyrolysis was a current hotspot with maximum number of publications in past 10 years (Fig. 2). Pyrolysis is a endothermic process of breaking organic compounds at high temperatures in an oxygen-free atmosphere resulting in production of bio-oil, gas, and solids.

This carbonised organic matter (BC) is produced from various biomasses with varying chemical and physical properties. These properties are crucial in thermal conversion processes, including proximate analysis, caloric value, constituents of fixed carbon, volatile components (Sakhiya et al., 2020), percentage of lignin, cellulose, and hemicelluloses (Chen et al., 2022), % and composition of inorganic material, bulk & true density, particle size, elemental percentages and moisture content (Sakhiya et al., 2020).

4. **Biochar modification techniques**

Although BC offers numerous benefits, the use of pure biochar in restoration has also faced certain obstacles like many inner spaces with clogged pores, and insignificant pore size. To address these challenges, there are several modification techniques available to modify the physicochemical characteristics of BC. They augment its efficacy in environmental applications (Chen et al., 2022). Typically, techniques for enhancing the functionality of biochar can be classified into three categories: physical, chemical, and biological alterations (Fig.4) (Zhang et al., 2022). These adjustments modify the characteristics of the pores, size of particles, surface area, functional groups, distribution elements, cation exchange capacity (CEC), charges, and ultimately improve its effectiveness (Duan et al., 2019; Chen et al., 2022; Medeiros et al., 2022).

4.1. Physical Modifications

The process of biochar physical activation entails carbonization, which takes place in an inert environment. The initial step involves subjecting unstructured regions of biomass to elevated temperatures, resulting in the permeabilization of pores. Two most widely used processes are steam and carbon dioxide activation. In the process of steam activation the water gas shift reactions occurs to reduce carbon content, leading to the creation of pores and the subsequent exposing of novel surfaces inside the biochar. Higher temperatures lead to an increase in the surface area of biochar, but, prolonged activation times can result in adverse consequence. While in carbon dioxide activation the pores are generated via the Boudouard reaction in wherein carbon dioxide undergoes dissociation to yield an oxygen surface complex and carbon monoxide (Sajjadi et al. 2019). Carbon monoxide production results in the deactivation of carbon sites. The hybrid technique results in a 2.7% reduction in surface area compared to steam activation (Sun et al. 2020). The utilisation of physical activation has been recognised as a potent method to augment the functionality of BC by exerting an influence on its features, including as surface functional groups, polarity, and hydrophobicity (Medeiros et al., 2022). Overall these physical methods are typically more straightforward and cost-effective compared to chemical activation methods (Akhil et al., 2021). Nevertheless, these modification approaches have certain disadvantages such as excessive energy consumption and prolonged activation time (Shaheen et al., 2022b). Chemical modification is widely regarded as the preferred choice for modifying BC because of these reasons.

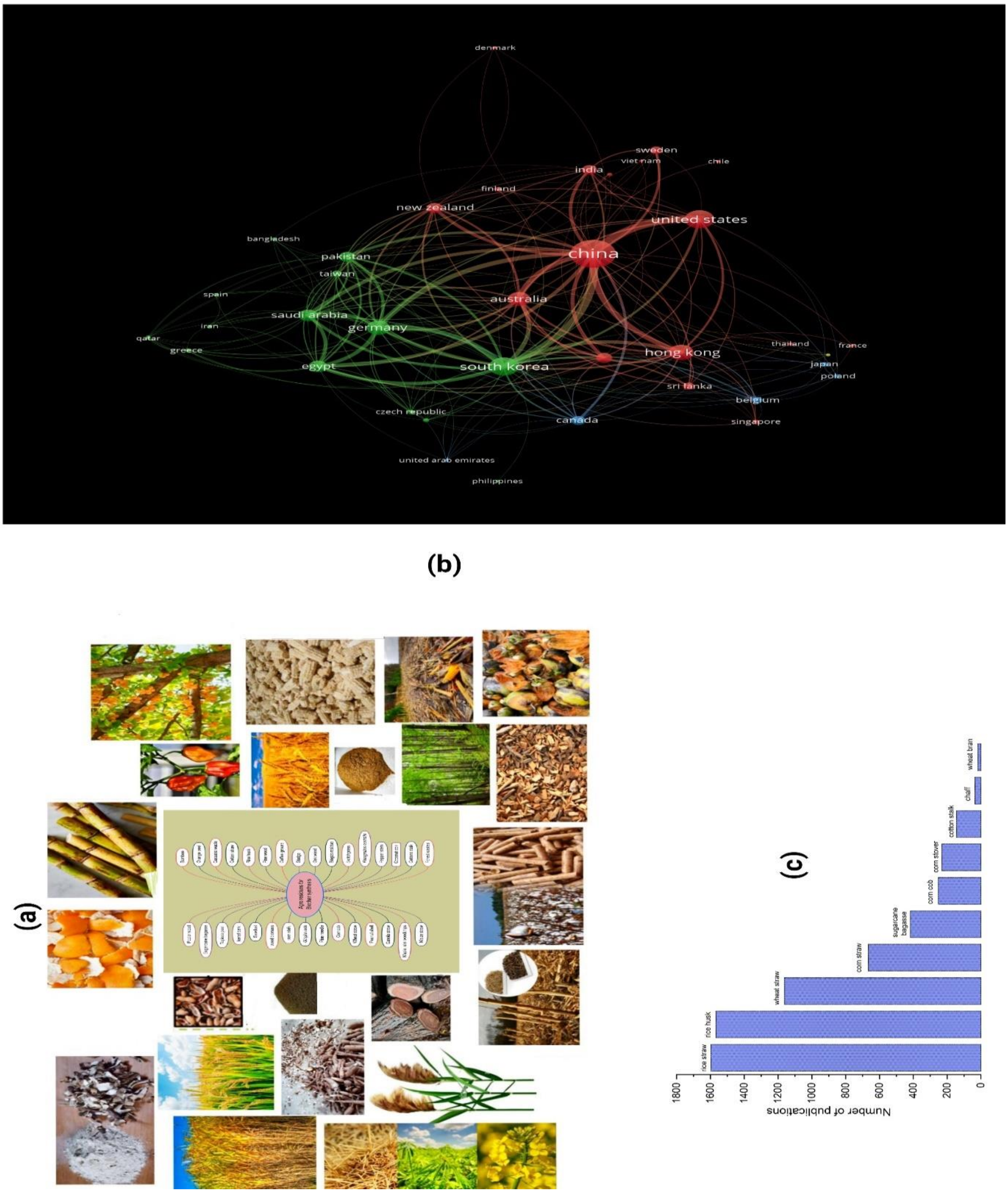

Fig. 1. (a) Agro-residues used for biochar preparation (b) countries wise VOS diagram for keyword "Biochar" and (c) order of no of publications on different agro-residues.

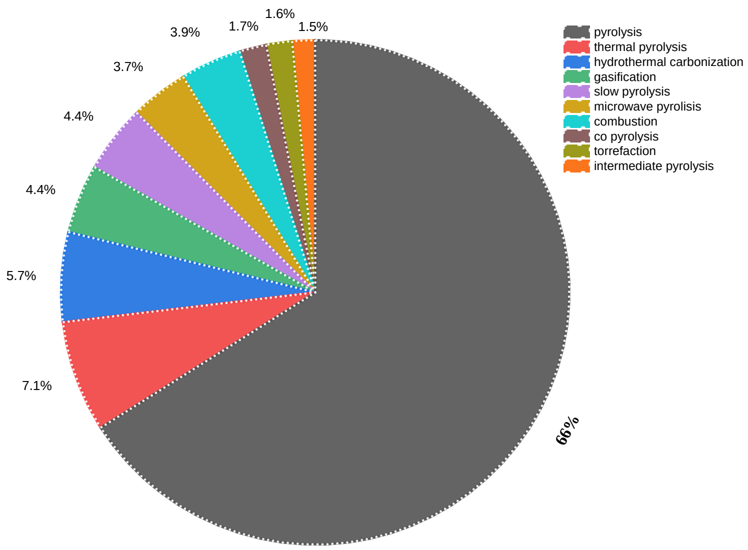

Fig. 2. Pi-chart of Biochar Preparation techniques used as per scopus.

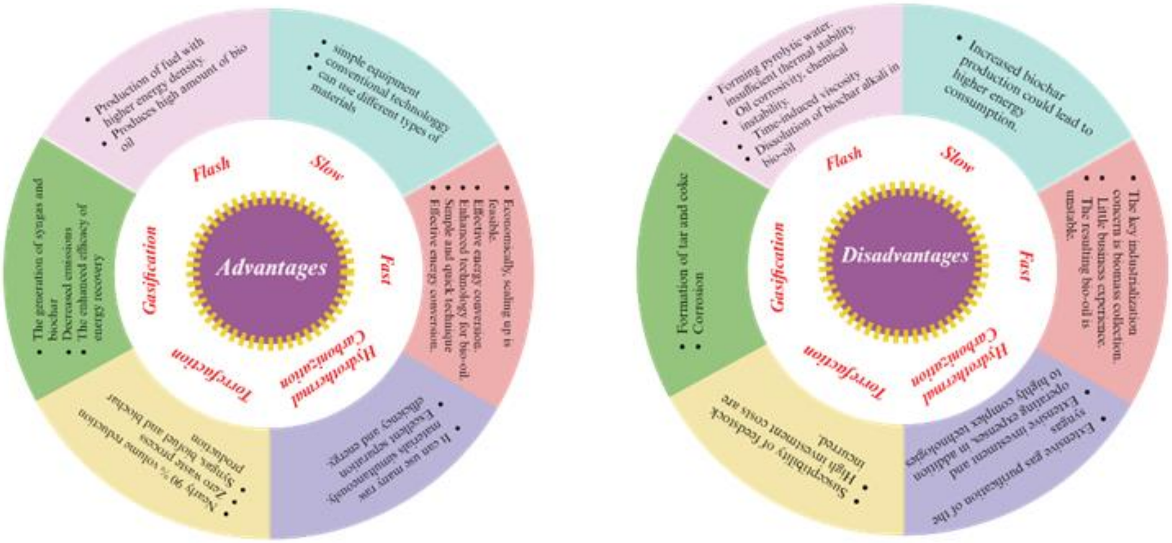

Fig. 3. Advantage and disadvantages of different techniques used for biochar preparation.

Microwave activation

Microwave activation can generate thermal energy for biochar activation. Conventional thermal treatment generates heat using fuel, whereas microwave treatment does so with less electricity. Microwave radiation can improve surface properties by generating molecular-level electromagnetic waves. Micropores are consistently higher in microwave-treated biochar than in furnace biochar. The molecules absorb microwave radiation and vibrate at a precise frequency, resulting in pores in the structure. Reservation of more polar groups resulted in a larger biochar yield compared to mufe furnace production (Akhil et al., 2021). This can be combined with other chemical activation techniques to produce composite biochar. The increase in surface area could be attributed to microwave radiation, which removes volatile.

compounds and ash. By this process, an increase in BC's pH, SA, CEC, water-holding capacity, and chemical properties, can be observed. Also, an increase in structural stability and a decrease in activation energy also observed (Paramsivan, 2022).

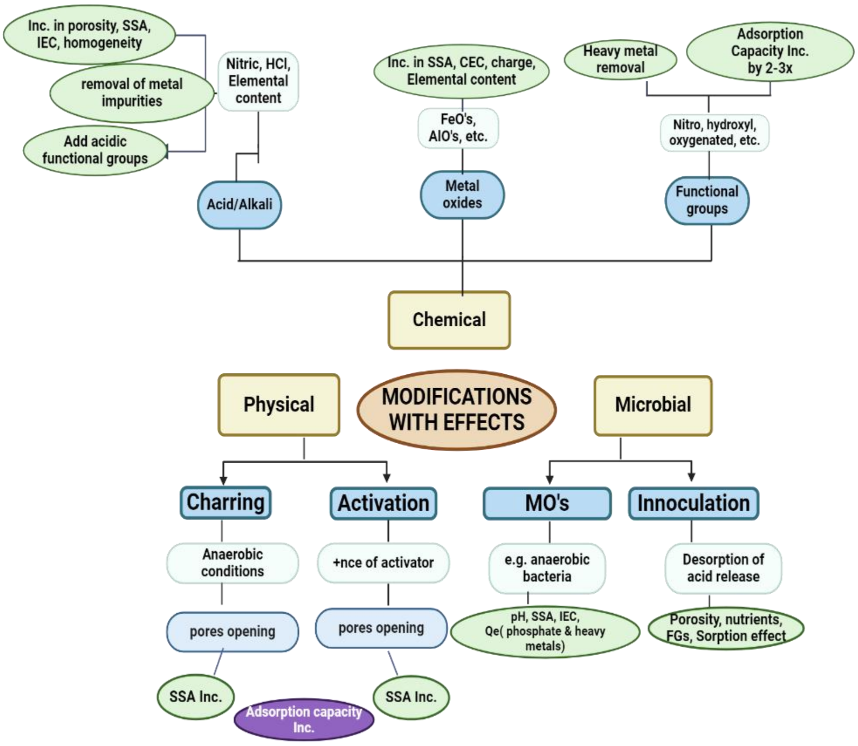

Fig. 4. Modification techniques for biochar with its effects.

Ball milling

Ball milling increases biochar pore characteristics and is appropriate for large-scale cleanup (Zhou et al., 2021). The ball milling technique enhances electrostatic, cation-π, and surface complexation. Milling biochar improves its adsorption capability over unmilled biochar (Lyu et al. 2020). Activating biochar with potassium bicarbonate boosts pore capacity by 100 times relative to pyrolyzed biochar and 28 times for magnetic activated biochar (Li et al., 2020). Increased temperature greatly enhances surface characteristics. Furthermore, disruption of oxygen-containing groups reduces biochar's carbon concentration. Ball milling method increases interior surface area by exposing pore networks while decreasing particle size. Unmilled biochar included micrometer-sized particles, but ball-milled biochar contained particles ranging from micro to nanometers (Gyanwali et al., 2024).

4.2 Chemical Modifications

This usually involves complex, expensive procedures and toxic reagents, and commonly used methods include manipulation of acids, bases, metal oxides, organic compounds, graphene, and other carbon-containing structures.

Acid, alkaline, and oxidant modifications

Acid treatment is to remove metals from the surface, and decreases pH which increases the remediation effect, mainly used acidic functional groups are phenolic, -COOH, etc. (Wang and Wang, 2019). The common acids used are nitric, HCl, phosphoric, sulphuric, etc (Zhou et al., 2021). While basic treatment enhanced aromaticity, and N/C ratio, but decreased % ratio in comparison with acid treatment. KOH and NaOH are mainly used bases (Duan et al., 2019). The use of oxidants provides thermal stability to BC and increased their affinity to bind pollutants. A method for modifying biochar with iron (Fe) is presented to enhance the efficiency of separating and recycling biochar (BC) for reuse (Huang et al., 2019). As iron (Fe) is the most frequently utilised metal, with manganese (Mn) being the next most generally used. The development of iron-modified biochar involves the utilisation of iron oxides (such as hematite and goethite), iron sulphide (FeS), and nano zero-valent iron (nZVI) (Lyu et al., 2020). Iron-modified biochar can be produced using co-pyrolysis (Yang et al., 2022a), precipitation (Yang et al., 2022b), thermal reduction, and ball milling techniques (Kumar et al., 2020). Mn has gained significant popularity due to its several benefits, such as its abundant availability, ease of use, and environmentally friendly nature (Shaheen et al., 2022b). Additional metals used for modifying biochar include magnesium (Mg) (Zheng et al., 2020), aluminium (Al) (Wang and Wang, 2019), copper (Cu) (Zhong et al., 2020), cerium (Ce) (Dong et al., 2020), lanthanum (La) (Wang et al., 2018), zirconium (Zr) (Rahman et al., 2021), bismuth (Bi) (Zhu et al., 2019), and others.

4.3 Biological Modifications

This is comparatively less researched than physical and chemical modifications, primarily because of its complex nature. Historically, anaerobic bacteria were employed to convert biomass into biogas and the resulting waste into BC. BC produced via this method demonstrated, among other characteristics, a strong ion exchange capacity, high pH, and a substantial SSA. Furthermore, it exhibited an exceptionally high adsorption capacity for phosphate and heavy metals (Ngambia et al., 2019). BC is a highly recommended carrier for microbial inoculation due to its advantageous properties, including a high porosity, nutrient abundance, cost-effectiveness, and ease of preparation. Based on research findings, living cells have the ability to synthesise an assortment of polymers and establish a biofilm on the BC surface, thereby promoting the adsorption procedure (Lin et al., 2021; An et al., 2022). Desorption is facilitated by microbial addition via acid release. The sorption influence of BC is enhanced by the abundance of functional sites, including amino, carbonyl, and hydroxyl groups, on the microbial surface (Wang et al., 2021).

5. Methods of characterization of synthesized Biochar

It is necessary to thoroughly characterize synthesized biochar in order to comprehend its physicochemical features and fully understand the fundamental mechanisms of each biochar's individual behaviours. Chemical and spectroscopic examination are the two most widely used analytical methods for biochar. With the right adjustments, conventional procedures employed for other environmental samples, including soil, can be utilised to evaluate chemical characteristics, elemental composition, Boehm titration, etc. (Bolan et al.2022). Different spectroscopic analytical techniques, as summarised in Fig.5, are in use for the detection of the presence, atomic structure, and specific diversification of metalloids within biochar (Li et al. 2020a; Yang et al. 2022b; Chen et al. 2022).

6. Physicochemical properties of biochar

The physical properties of BC are affected by the nature of the biomass and the conditions of pyrolysis (Table 1). For commercial use, biochar's pore-size distribution is essential. Biochar has a total pore volume made up of macropores, mesopores, and micropores. Mesopores play a key role in adsorption processes, whereas micropores increase the surface area of biochar and effectively adsorb small molecules. By extending biomass pyrolysis at higher reaction temperatures, releasing volatile content, and slowing pyrolysis, micropore volume can be increased. Chars with greater surface areas are produced by lignin cores that are aromatic, as well as by aliphatic alkyls and ester groups (Tomczyk et al., 2020). Bulk and solid densities of soil are altered by addition of biochar. High pyrolysis temperatures increase biochar's solid density, by shrinking and carbonizing the matrix. Biochar decreased the bulk density due to drying and carbonizing the biomass. Biochar quality depends on mechanical strength to survive environmental wear and tear. Biochar’s solid density, aromaticity, and crystallinity determines the mechanical strength. Fruit stones/pits and nut shells, which have low ash and high lignin, are better for biochar formation due to their mechanical qualities (Panahi et al., 2020). By chemically transforming biomass into biochar, every pyrolysis process can produce biochar with a variety of useful properties. While the alkalinity grows linearly with increasing pyrolysis temperature, the charcoal production decreases exponentially. Because of the minerals they contain, biosolids have the highest cation exchange capacity, and this capacity decreases as the pyrolysis temperature rises. Higher pyrolysis temperatures result in larger quantities of volatile matter because their content decreases linearly with increasing temperature, while the content of carbon diminishes at a slowerpace.

7. Potential advantage of applying biochar on soil improvement

One major environmental concern is soil pollution from both organic and inorganic contaminants. Excessive usage of fertiliser to keep up with the growing demand for food due to population growth is also a significant cause of soil pollution and degradation. To control soil pollution, several techniques have been used, including membrane filtration, coagulation, ion exchange, phytoremediation, and precipitation. These techniques might produce waste that is contaminated; however, they are not necessarily economical. The application of biochar materials to reduce soil pollution and to increase its fertility as well, has been studied by researchers. It has been demonstrated that biochar's high permeability may effectively absorb suspended particulate matter, capture hazardous components, and lessen the negative impacts of soil acidification (Gyanwali et al., 2024; khalaf-alla et al., 2024). But as a perfect fertilizer, BC produced by direct thermochemical processing of biomass feedstocks typically lacks essential nutrients. To increase fertilizer efficacy, BC has been modified to form a biochar based slow-release fertilizer (B-SRF) (Rombel et al., 2022).

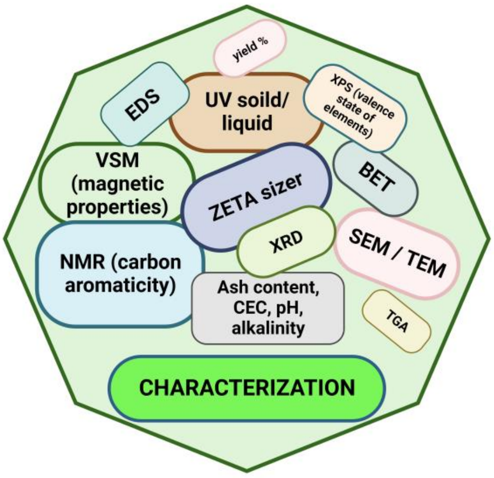

Fig. 5. Different techniques used for characterization of biochar.

TABLE 1. The physicochemical properties of biochar of different agro-residues.

Feedstock	Temp (C)	FC (% db.)	VM (% db.)	Ash (% db.)	C db.)	H (% db.)	O (% db.)	N (% db.)	Reference(s)
Corncob		12.45	82.38	5.04	47.4	5.8	50.1	0.6	Wang et al. (2022)
Corn stalk		14.68	82.42	2.91	43.6	5.8	49.4	1.1	
Flax straw		11.4	81.3	2.9	44.4	6.7	46.5	1.4	Mukhambet et al. (2022)
Canola stalk	350-605	_	_	_	51.7	2.64	36.38	1.44	Yang et al. (2021)
Rice straw	300-600	_	_	_	58.8	1.53	11.72	2.02	Zhang et al. (2020)
Rice straw		10.06	76.87	13.07	40.06	5.47	40.23	0.69	Hong et al. (2020)
Cotton stalk		10.17	82.38	7.45	43.95	5.81	41.12	1.12	
Barley straw		11.83	78.8	6.43	45.41	6.1	46.21	1.18	Ahmed and Hameed, (2018)
Corn stover		8.93	82.21	8.86	43.28	5.92	39.32	1.96	He et al. (2018)
Rape stalk		7.49	86.09	6.42	43.92	5.92	42.54	0.49	
Sugarcane bagasse		8.87	81.23	2.51	49.26	5.26	44.95	0.43	Ahmed et al. (2018)
Rice husk		11.44	73.41	15.14	41.92	6.34	–	1.85	Biswas et al. (2017)

A bibliometric study of global scientific publications relevant to biochar research was done, offering insight into the number of articles published (Fig.6). This comprehensive bibliometric analysis will aid individuals and research organisations in identifying future research directions and comprehending global biochar research trends.The Scopus database was used, and a total of 9650 publications published up to March, 2024 were retrieved with the keywords biochar and soil, and 79 articles have been published for the keyword biochar-based slow-release fertiliser and soil. It was discovered that there were no articles on these keywords biochar and soil before 2007; on biochar-based slow-release fertiliser and soil before 2017. Biochar's effects on vegetation, soil, and the ecosystem are still the subject of ongoing research organisations in identifying future research directions and comprehending global biochar research trends. Biochar's effects on vegetation, soil, and the ecosystem are still the subject of ongoing research.

When it comes to agricultural output, fertilisers are the lynchpin. It is now obvious that in order to fulfil the world's food demands, agricultural output needs to be increased and for that the use of fertilisers is essential, however their efficiency must increase for their sustainable use. Even though nitrogen has a utilisation efficiency of around 30–40% and phosphorus of 12–16%, it is still the most used nutrient for healthy soil fertility and plant growth. There has been a growing awareness of the environmental problems caused by chemical fertilisers due to their extensive use. It is estimated that between 40 and 70% of the N, 80 to 90% of the P, and 50 to 70% of the K fertilisers end up in the environment (Duhan et. al., 2017; Wang et. al., 2022). Consequences of excess use of nitrogen fertiliser includes, low nitrogen utilisation efficiency, high economic costs, environmental pollution (Luo et. al., 2021), NH_3 volatilization, N_2O emissions, and NO_3 leaching.

The usage of conventional fertilisers in agriculture, leads to soil and groundwater contamination. The fertility of the soil gradually declines, provide quick profits at the expense of the long haul, harmful or destructive in nature with loss of nutrients leading to affect microbes or soil biota. Even plants stress out as these fertilizers release

Biochar is a nutrient-rich substance, and its application considerably improves soil fertility by supplying important nutrients and maintaining an appropriate pH (Khan et al., 2020). Effects of applying biochar on crop growth and yield has been shown through Table 2.

8. Biochar as a slow-release fertilizer (B-SRF)

nutrients at once and in many cases plant burning has seen. So, by switching to organic or SRFs can alleviate or at least lessen these issues. The VOS based country wise analysis of biochar as slow release fertilizer depicted that China has highest number of research in this area (Fig 7).

To prolong the time that plants have access to a nutrient, slow-release fertilisers (SRFs) and controlled-release fertilisers (CRFs) use encapsulated or barely soluble compounds. When applied in conjunction with conventional fertilisers, SRFs and CRFs lessen stress and particular toxicity while increasing nutritional synergy. Fertilisers of the SRF/CRF type can be applied once and continue to supply nutrients all through the growing season, which helps farmers save money. They support the soil microbiome, leading to a proliferation of different bacterial species and improve the nitrogen use efficiency (NUE). The exceptional properties of BC provide a solid basis for the development of SRFs based on BC (Fig.7). Several methods have been proposed to produce effective biochar-based SRFs, such as impregnation (An et al., 2022), encapsulation (Sim et al., 2021), granulation (Zheng et al., 2017), co-pyrolysis, etc represented in Fig.8**.**

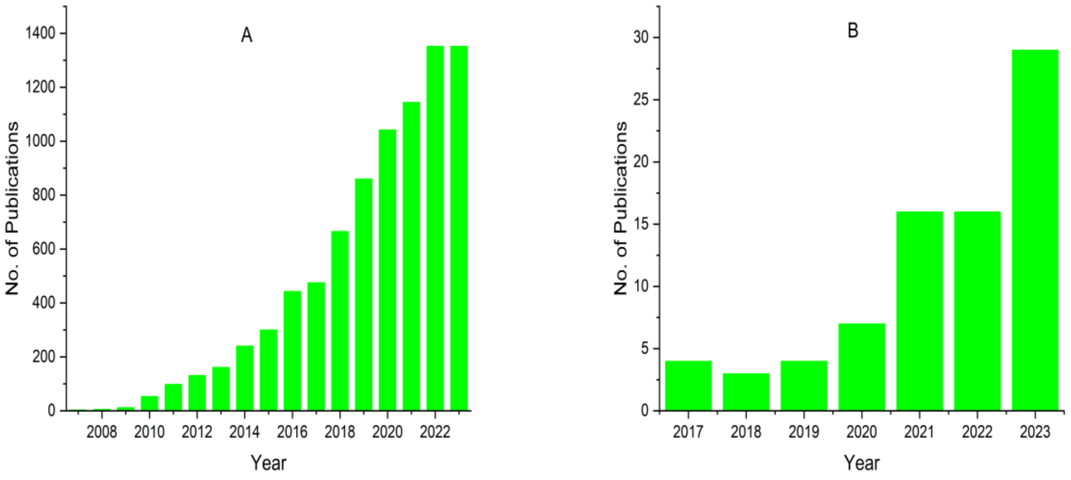

Fig. 6. Bibliometric data representation of number of articles published in Scopus Keyword (A) biochar and soil; (B) biochar based slow-release fertilizer and soil.

TABLE 2. Studies related to effect of applying biochar in soil on crop.

Feedstock	Pyrolytic Temp °C	Crop	Application rate	Positive effects on crop growth and yield	Reference
Sugarcane bagasse		Maize	0-6 t ha^{-1}	Improvement in plant roots traits, leaf area, plant growth, morphological and yield-related parameters. Plant height, number of grains per cob, grains and biological yield decreased with biochar addition 6 t ha^{-1}	Minhas et al., 2020
Straw		Maize	0-36 t ha^{-1}	Improved maize crop photosynthesis, soil nitrogen, and chlorophyll.	Khan et al., 2022
Maize stover	550	Maize	0-47.25 t ha^{-1}	31.5-47.25 t ha^{-1} increased maize straw (38.6-71.3%) and grain (20.9-25.5%) soil phosphorus absorption.	Cao et al., 2020
Straw	----	Wheat, maize	0-8 t ha^{-1}	Increased crop biomass and yield (8 t/ha optimum)	Hu et al., 2021
Agro residue		Tomato	0, 5 and 10 t ha^{-1}	By using 10 tonnes of biochar per hectare, tomato yield increased by 30% and harmful substances were reduced.	Almaroai and Eissa, 2020
Straw		Wheat Maize	0-11.25 Mg ha^{-1}	(2.25-6.75 Mg ha−1) enhances crop yield, soil productivity, and regulates N cycling.	Xie et al., 2021
Rose and teak wood		Rice	16 t ha^{-1}	Top soil saturated hydraulic conductivity and xylem sap flow increased.	Kochanek et at., 2022
Peanut hull		Quinoa	0-200 t ha^{-1}	Better N-P fertilisers, higher grain yields. Growth, production, drought tolerance, leaf-N, chlorophyll, and proline reduced.	Zhang et al., 2022
Apple wood	400	*O. Viciifolia*	0-4% BC (400g soil)	Decreased oxidative damage, higher morphological growth, osmolytes, and antioxidant enzyme activity.	Roy et al., 2022
Citrus wood		*Tomato* *Peper*	1%-5% (w/w)	Not significant result	Kader et al., 2022
plant residues	400	Rice	10 t ha^{-1}	significantly improves rice plant nutrition, water content, soil quality, and physiological characteristics, thereby enhancing water stress tolerance.	Hafez et al., 2024

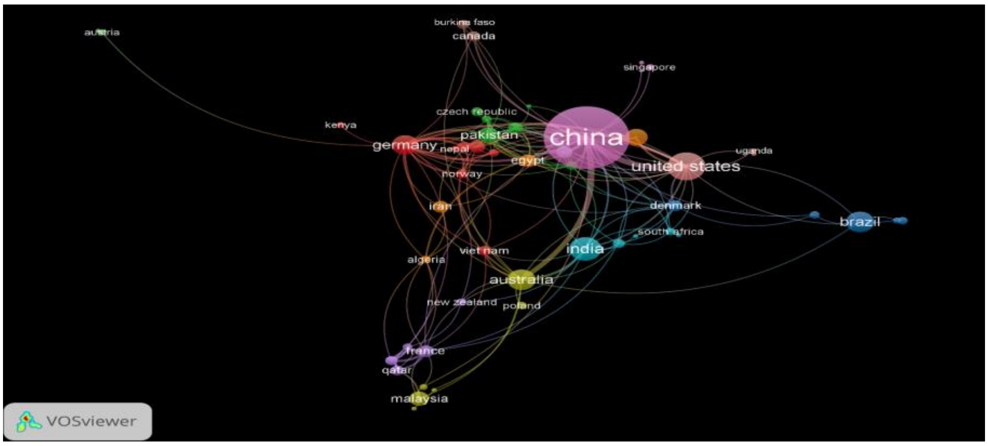

Fig. 7. VOS country wise diagram by using the word biochar and slow release fertilizer.

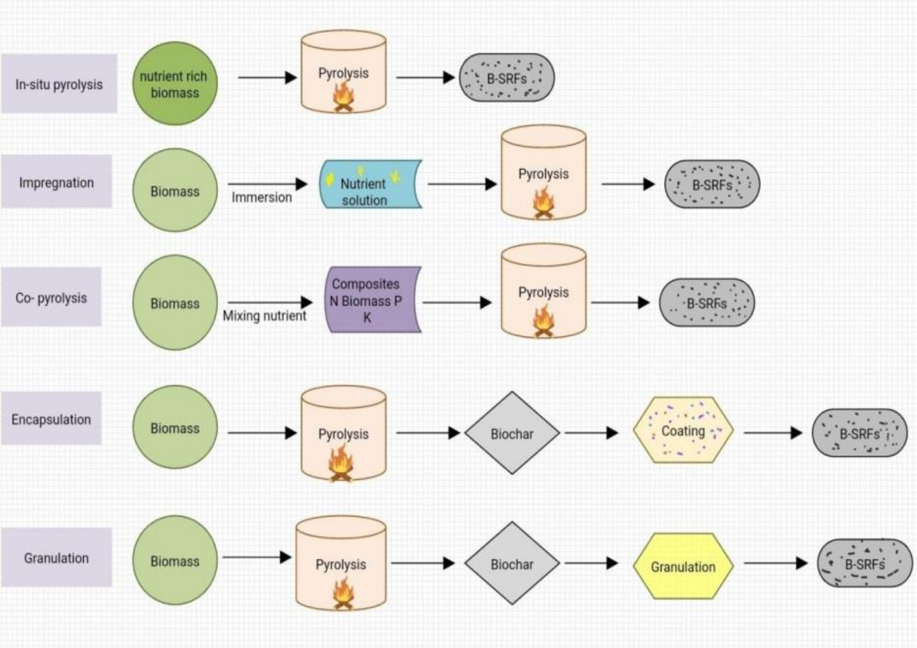

Fig. 8. Different methods for the synthesis of B-SRFs.

Some biochar-based SRFs fabricated by different methods and their slow-release performance is shown in Table 3. Investigating the sustainable integration of slow-release fertilizers derived from biochar in agricultural practices is imperative for optimizing nutrient management. The accompanying diagram (Fig.9) delineates the key advantages and challenges associated with this innovative approach. Biochar-based fertilizers offer promising benefits such as enhanced nutrient retention, reduced leaching, and potential carbon sequestration (Dai et. al., 2020). However, the diagram also highlights considerations such as the initial production costs and variations in nutrient release. A comprehensive understanding of these pros and cons is crucial for informed decision-making and the effective implementation of biochar-enhanced slow-release fertilizers for sustainable agriculture. Studies related to application of biochar as SRF has been compiled in Table 4.

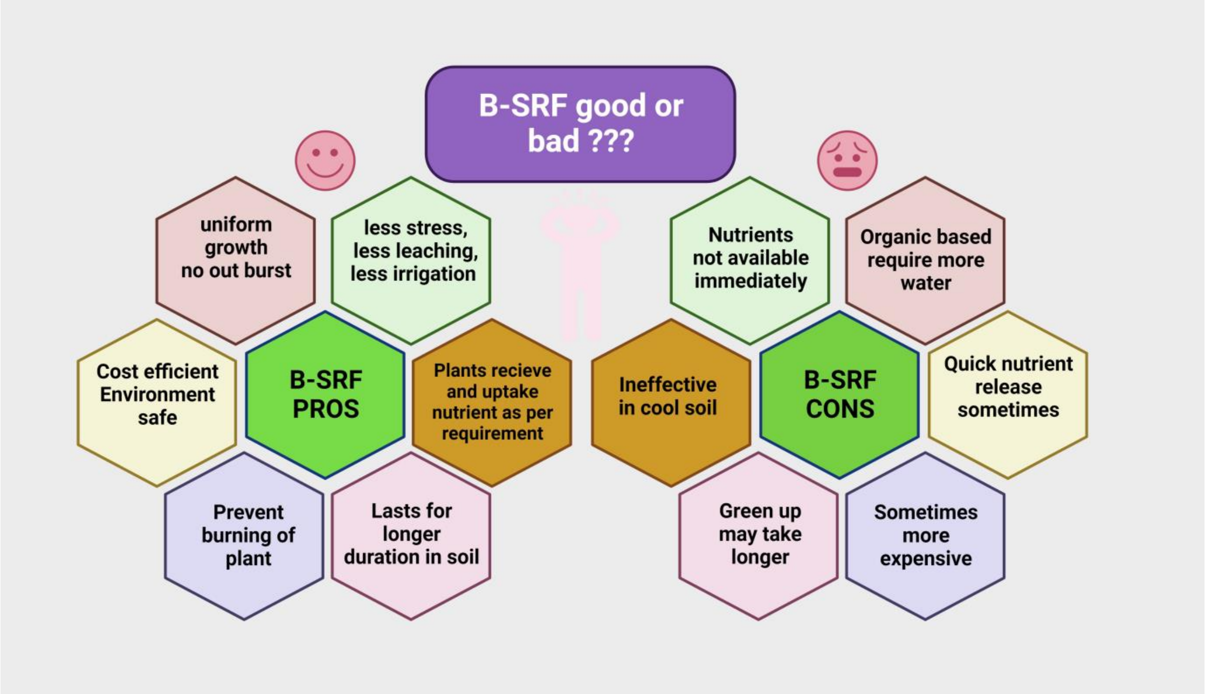

Fig. 9. Pros and cons of using SRF.

TABLE 3. Studies related to performances of different biomaterial as SRF.

S.No.	Biomaterial Based fertilizers	Preparation methods	Biomaterial and compounds as fertilizers	Nutrients	Slow-release performance	References
1	Phosphorus based-SRF	Pyrolysis followed by Impregnation	**Biomaterial-** cornstover **Fertilizer-** KH_2PO_4	22 mg/g P	P release was 40% after 5 d	Sepúlveda-cadavid et. al., 2021
2	P-SRF (CHB) Biochar from coffee husk (PLB) Biochar from poultry litter	Co Pyrolysis	**Biomaterial-** Coffee husk & poultry litter **Fertilizer-** Cnc.phosphoric acid & MgO.	201mg/g Phosphorus in Coffee husk BC, and 1780 mg/g Phosphorus in Poultry Litter BC	P release 6.47% (CHB) and 8.99% (PLB) within 1hr	Da Silva Carneiro et. al., 2021
3	P-SRF	Impregnation Pyrolysis	**Biomaterial-** Cotton straw, **Fertilizer-**NaAlg, $MgCl_2$ & $Mg_3(PO)_4$	0.2g SRF/ 200g soil	100% P release was in 60 days	An et. al., 2020
4	Magnesium filled Biochar as a fertiliser	Co-pyrolysis followed byImpregnation	**Biomaterial-** Corn stalk **Fertilizer-** mixture of biogas effluent and KH_2PO_4	200 mg per g Nitrogen & 381 mg per g Phosphorus	Nitrogen---18% and Phosphorus---16% were released in 48 h	Luo et. al., 2021
5	N-SRF	Pyrolysis Encapsulation Granulation	**Biomaterial-** pine biomass Activation by H_3PO_4 **Fertilizer-** Ca-LS liquefied paraffin wax	N content 26.74-343.2 mg/g	NH_2CONH_2 released in Aq. medium was 61 to 90% in 72h.	Bakshiet. al., 2021
6	Phosphorus SRF biochar based with bentonite modification	Impregnation	**Biomaterial-** Cotton straw, Hydrogen-bentonite, Nitrogen-bentonite, and hydroxide bentonite **Fertilizer-** KH_2PO_4	Phosphate was 245.56 mg/g	Phosphorus release in 15 days was 72.6%	An et. al., 2021
7	P fertlizer	Pyrolysis Encapsulation Granulation	**Biomaterial-** Wood chips **Fertilizer-** with blending (B) or coating (C) of superphosphate	Total P was 154-199 mg/g	Total Phosphorus release in 1.5 hours was 82% & 36% for B and C biomaterial.	Pogorzelski et. al. 2020
8	Biochar based Nitrogen and Phosphorus as a fertilizer	Pyrolysis followed by Impregnation	**Biomaterial-** oil palm kernel shell **Fertilizer-** NPK, NH_4NO_3, KH_2PO_4	24.2 mg/g NH_4NO_3 + 5mg KH_2PO_4 per 87.7mg BC per column.	NO_3 release was seen 52.9% & 77.4% --- NH_3 and 55.2 % --- PO_4^{-3} after 1h.	Dominguez et. al. 2020
9	N and P fertilizer	Pyrolysis Impregnation	**Biomaterial-** wheat straw and shell **Fertilizer** - Mg^{2+}/ PO_4^{-3}/ NH^{4+}	N 4.93% and P_2O_5 22.19%	Release of Nitrogen and Phosphorus after 84d was10.62% & 6.84% in DW, and 59 32% and 59.12% in solution of citric acid.	Hu et. al., 2019

TABLE 4. Effect of slow release fertilizer on agronomic performance.

Crop	Feedstock	Pyrolysis temp (°C)	Fertilizer	Effect of growth and yield	References
Ipomea batata	Hardwood	500	K	Enhanced vine length, leaves, tubers, and weight.	Adekiya et al. (2022
Zingiber officinale	Bamboo	450, 600	K	Greater root mass and plant height	Farrar et al. (2021)
Zingiber officinale	Hardwood	580	NPK	Improved soil physical and chemical qualities, growth, and ginger yield (number and fresh rhizomes) compared to control.	Adekiya et al. (2020)
Solanum tuberosum	_	_	N, P, K	High tuber yield (35.76 t/ ha) and quality metrics like 25.33% dry matter and 1.12 specific gravity.	Mollick et al. (2020)
Maize	Potato straw	450	N, P	higher increases in shoot and root biomasses	Khalil et al., 2023

9. Conclusion ands Future Prospective

Agricultural residue-derived biochar is a sustainable waste management and soil enhancement technology that converts agricultural byproducts into beneficial soil nutrients. The review examined the essential physicochemical features of biochar, such as surface area, porosity, pH, and nutrient content, which are important in assessing its appropriateness for soil and crop applications. Biochar's potential to improve soil structure, increase water retention, boost nutrient availability, and encourage beneficial microbial activity makes it an important sustainable soil supplement. Furthermore, the role of biochar in carbon sequestration helps to mitigate climate change, emphasising its environmental benefits. In overall, agricultural residue-derived biochar holds great promise for sustainable agriculture. The biochar based SRFs are also a great solution to traditional fertilizers towards environment and community. Creating low-cost technologies for producing high-quality biochar from various agricultural residues and organic waste can improve the efficiency and scalability of biochar manufacturing. Continued research and development in biochar technology and practical applications will be required to realize its full potential and achieve long-term agricultural and environmental advantages.

Declarations

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