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Review Article

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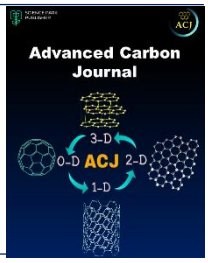

Agricultural residues in India: Sustainable valorisation into activated biochar for multifunctional environmental applications: A review

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Abstract

In India, agricultural residues are abundant sources of renewable carbon, but they are poorly managed, mostly through open field burning, which results in the loss of potentially valuable biomass and environmental waste. The transformation of these residues into engineered biochar will offer a promising resource recovery and carbon materials production route. This review critically analyses the processing of Indian agricultural residues into activated biochar and focuses on relationships between the feedstock, thermochemical conversion, activation, physicochemical characteristics, and environment. The spatial and temporal setting of agricultural-residue burning is discussed based on the satellite observed data, which emphasize the distribution and variability of the burning of wheat and paddy/rice residues in major hotspot areas. Pyrolysis and other thermochemical conversion routes are analysed and the impact of process parameters on the yield, carbon structure, surface chemistry, porosity, and stability of biochar is discussed. Special emphasis is placed on physical, chemical, biological, and hybrid activation strategies to tailor the pore architecture, functional groups, surface charge, and adsorption properties. The removal of heavy metals from water, nutrients, dyes, pharmaceuticals, pesticides, and other emerging contaminants; soil remediation; carbon management, catalysis; and other environmental systems are critically assessed for their potential environmental applications of activated biochar. The review also identifies the bottlenecks of consuming the activating agent, demand of energy, washing and wastewater generation, energy regeneration, environmental safety, cost and scale-up. Future studies should focus on: green and low activation energy, integrated conversion activation process, standardized characterization and performance assessment, regeneration studies, life cycle and techno-economic evaluation, and scalable production of application-specific activated carbon materials. In summary, the use of biochar generated from agricultural residues is a promising approach to the development of functional, high-value carbon materials and for sustainable management of residual materials and circular use of carbon.

Keywords: Agricultural residues; Activated biochar; Biomass valorisation; Residue burning; Thermochemical conversion; Biochar activation; Environmental remediation; Circular bioeconomy

1. Introduction

Crop leftovers, such as straw, husks, stalks, shells, bagasse, and other lignocellulosic materials, are produced in significant amounts during agricultural production. These leftovers, which contain cellulose, hemicellulose, and lignin that can be transformed into commodities with additional value, are a renewable biomass resource rather than just

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agricultural trash. However, crop type, agricultural productivity, harvesting methods, and geographic conditions all have a significant impact on the amount and makeup of residues. Because of variations in crop coverage, residue-to-product ratios, moisture assumptions, and definitions of gross and surplus residues [1–3], reported estimates of agricultural residue generation vary between research. This variation emphasizes how crucial it is to view agricultural wastes as a diverse, geographically dispersed resource as opposed to a single, homogeneous trash stream.

Cereals, pulses, oilseeds, sugarcane, cotton, and other crops produce a variety of residues in India, one of the world's leading agricultural producers. Major food grains, oilseeds, and commercial crops continue to be produced at high levels, according to recent official agricultural statistics [4], offering a significant and geographically varied feedstock base for residue valorization. However, their current uses, such as home fuel, livestock feed, soil incorporation, and other agricultural or industrial applications, affect the availability of leftovers for conversion into value-added products [2, 3, 5]. Residues that cannot be practically or economically collected may be burned outdoors in a number of agricultural areas. This practice continues to be a significant residue-management concern in India, especially in situations where farmers' management decisions are influenced by labor restrictions, residue characteristics, short intervals between harvesting and the next crop, and a lack of economically viable alternatives. The spatial distribution of agricultural-residue resources and associated burning pressure in India is illustrated in Figure 1a, 1b, and 1c. Recently Consortium for Research on Agroecosystem Monitoring and Modelling from Space (CREAMS) observations further demonstrate the spatial concentration and temporal variability of wheat- and paddy/rice-residue burning across major hotspot regions, highlighting the persistence of residue burning as an important biomass-management challenge.

Inadequate residue management can have negative effects on the ecosystem and lead to the loss of potentially valuable biomass. In addition to releasing particulate matter and gaseous pollutants, open-field burning discharges some of the carbon and nutrients from the residue back into the atmosphere instead of keeping them in agricultural or industrial systems [6, 7]. Additionally, soil biological characteristics, nitrogen cycling, and organic matter may be impacted by repeated fire [3, 7]. The need for residue-management techniques that simultaneously lessen environmental impacts and recover the material and energy value of agricultural biomass has grown as a result of these effects. As a result, methods like composting, anaerobic digestion, bioenergy production, and thermochemical conversion have drawn more attention to the valorization of agricultural residues [3, 5]. The environmental and health consequences of agricultural-residue burning, along with the major residue-burning hotspots and key pollutants released during combustion, are summarized in Figure 2.

Among these methods, turning agricultural waste into biochar offers a desirable option to create a substance high in carbon while keeping biomass from being burned or disposed of carelessly.

Among these methods, turning agricultural waste into biochar offers a desirable option to create a substance high in carbon while keeping biomass from being burned or disposed of carelessly. Biochar produced through thermochemical conversion, notably pyrolysis, has been researched for soil amendment, carbon management, adsorption, and other environmental applications [8–10].

The content of the feedstock and the processing parameters - such as temperature, residence time, and heating conditions - have a significant impact on the characteristics of biochar. As a result, the carbon stability, ash content, surface chemistry, pore structure, and contaminant-interaction behaviour of biochar made from various agricultural residues can differ significantly [8, 9]. This is important because a capable soil amendment biochar is not necessarily a good biochar for efficient pollutant adsorption.

Another method for modifying the physicochemical characteristics of biochar for uses is activation. Physical, chemical and combination activation techniques can change the characteristics of the biochar surface - such as the shape, area and functional groups on the surface - which will consequently influence its interactions with pollutants and environmental matrices [11, 12]. Physical activation by steam, CO_2 or other gases can be used to increase porosity by the application of controlled heat treatment, while chemical activation using alkaline and acidic reagents can be used to promote surface functionalisation and pore growth [11, 13]. The performance of pyrolysis products, however, will depend

on the properties of the feedstock, the pyrolysis history, the activation conditions, and the intended use. It is therefore necessary to consider activation as a material engineering method that can be used to alter the structure and surface chemistry of biochar produced from agricultural residues to give it environmental properties rather than only to create a large surface area.

Although the issues related to the burning of agricultural residues and their environmental impacts have been discussed [5, 6], along with the production and use of biochar [8, 10] and agricultural-residue management in India, an integrated evaluation is still favourable [3, 6]. There is a particular need to develop a more critical understanding of the links between feedstock and thermochemical processing, activation, and final material properties, and environmental performance. Furthermore, any of the environmental benefits of using activated biochar should not be overlooked but rather balanced against the practicalities of using an activating agent, the need for washing, the generation of wastewater, biochar regeneration, energy requirements, cost and scalability. [11-14].

This paper explores the conversion of Indian agricultural residues into activated biochar through a critical analysis of the process starting from the feedstock selection, biochar production, activation, biochar modification, and finally environmental applications. Specifically, the review examines (i) availability and properties of major agricultural residues in India; (ii) thermochemical processing of biochar production and its effects on the biochar properties; (iii) biochar activation methods (physical, chemical, and hybrid) and their influence on biochar pore structure and surface chemistry; (iv) environmental applications of activated biochar: mechanisms and efficiency; and (v) sustainability, scalability, and research challenges for translating laboratory-scale activated biochar into practical applications. The review focuses on the sustainable transformation of the agricultural residues into the synthetic carbon materials from the feedstock, processing, and structure-function perspectives.

2. Lignocellulosic biomass

The use of lignocellulosic biomass has caught the interest of many people because it is abundant, renewable, and flexible as a feedstock to produce materials in a sustainable manner. It is mostly the by-product of agriculture and forestry and is a very good precursor for biochar production. The nature, chemical make-up, and physio-chemical properties of lignocellulosic feedstock and the major conditions of thermochemical processing have a significant impact on the yield, carbon content, and structure of final biochar.

Structurally, lignocellulosic biomass is made up primarily of cellulose (25-50%), hemicellulose (15-30%), and lignin (5-25%), but the proportion depends on species, growth conditions, and harvesting methods. Cellulose is a linear polymer of β-D-glucopyranosyl units, which is a source of rigidity and tensile strength because of the crystalline-amorphous microfibril structure [15-17]. Hemicelluloses are amorphous branched heteropolymers of sugars, galactose, glucose, and mannose, that provide flexibility between cellulose and lignin [18-20]. Lignin, being a highly cross-linked aromatic polymer, is resistant to microbial attack, hydrophobic, and provide structural rigidity of approximately 25% of hardwoods and 33% of softwoods [21-23]. Moreover, lignocellulosic biomass is also composed of minor organic components: proteins, terpenes, lipids, resins, and saponins, and inorganic ash fractions, which can be extracted by polar or non-polar solvents [23, 24]. These components together influence the thermal degradation characteristics, aromaticity, and structural stability of the carbon-rich biochar metrics [25, 26].

2.1. Potential for biochar production

Lignocellulosic biomass is considered one of the most abundant, inexpensive, and easily available feedstocks to produce biochar. This is remarkable, as it is both economically viable and environmentally friendly [27, 28]. The lignocellulosic biomass has several clear benefits compared to other biomass resources like animal wastes, food industry by-products, sewage sludge, and municipal solid wastes: lower moisture content, lower ash content, and relatively simpler chemical composition. Additionally, lignocellulosic biomass pyrolyzed biochar usually surpasses biochar derived from other sources. Some of its advantages are enhanced surface properties, fewer pre-treatment requirements, and larger applications in environmental and agricultural fields [29].

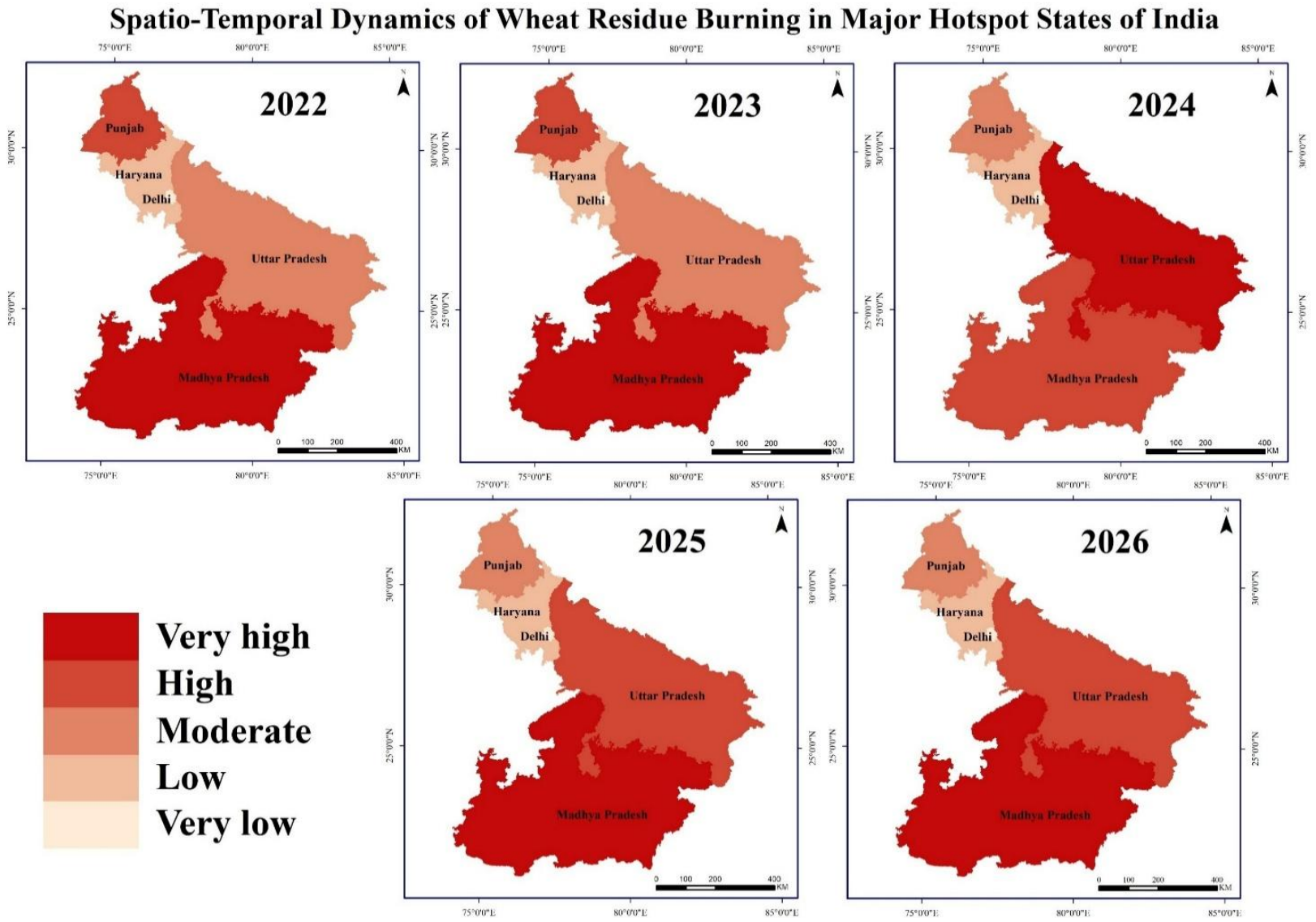

Figure 1a. Spatio-temporal dynamics of wheat-residue burning in major hotspot states of India, 2022-2026. Annual distribution of satellite-detected wheat-residue burning events during the April-May residue-burning season across the selected major hotspot states. [**Source**: ICAR-IARI-CREAMS]

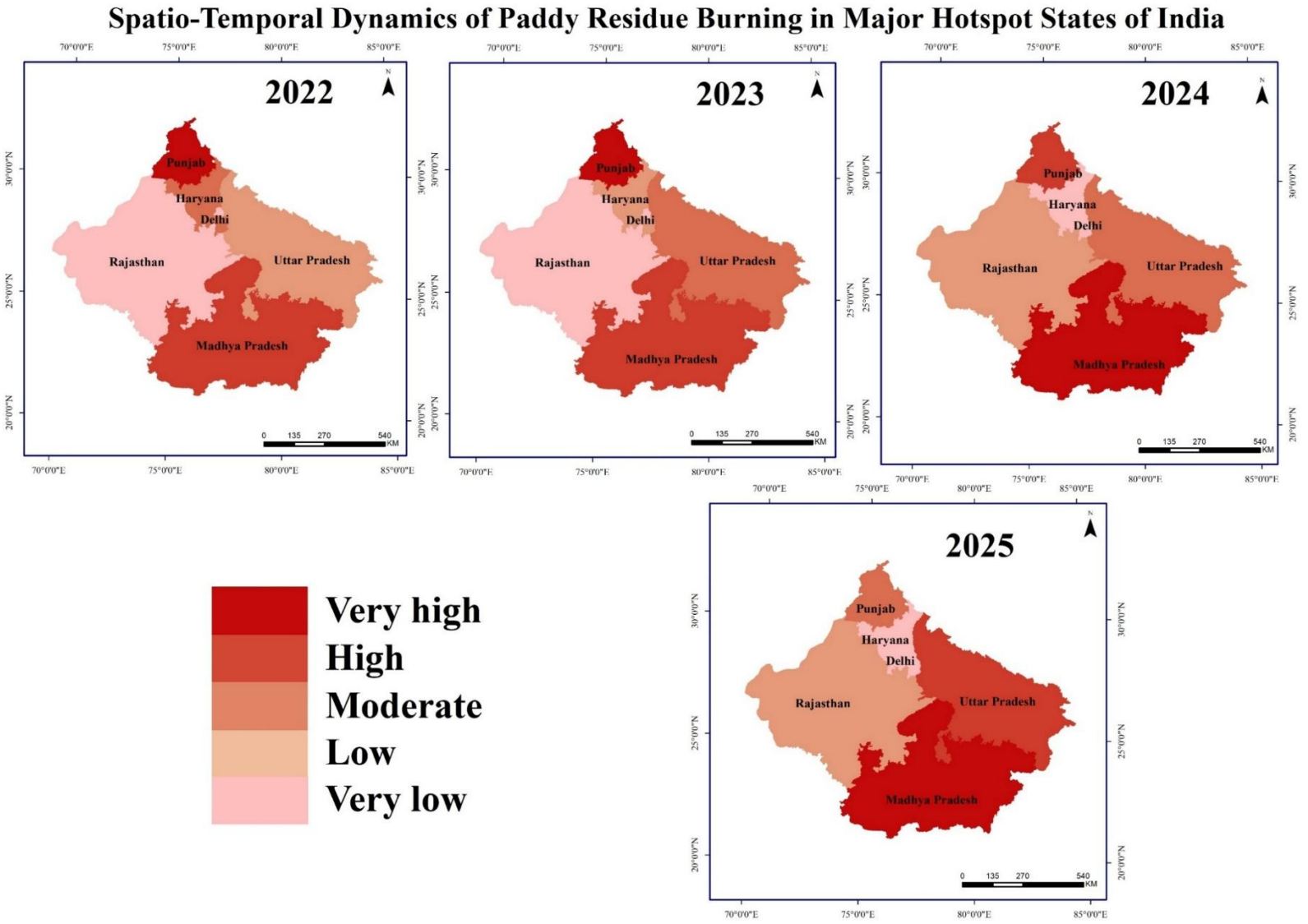

Figure 1b. Spatio-temporal dynamics of paddy/rice-residue burning in major hotspot states of India, 2022-2025. Annual distribution of satellite-detected paddy/rice-residue burning events during the September-November residue-burning season across the selected major hotspot states. [**Source**: ICAR-IARI-CREAMS

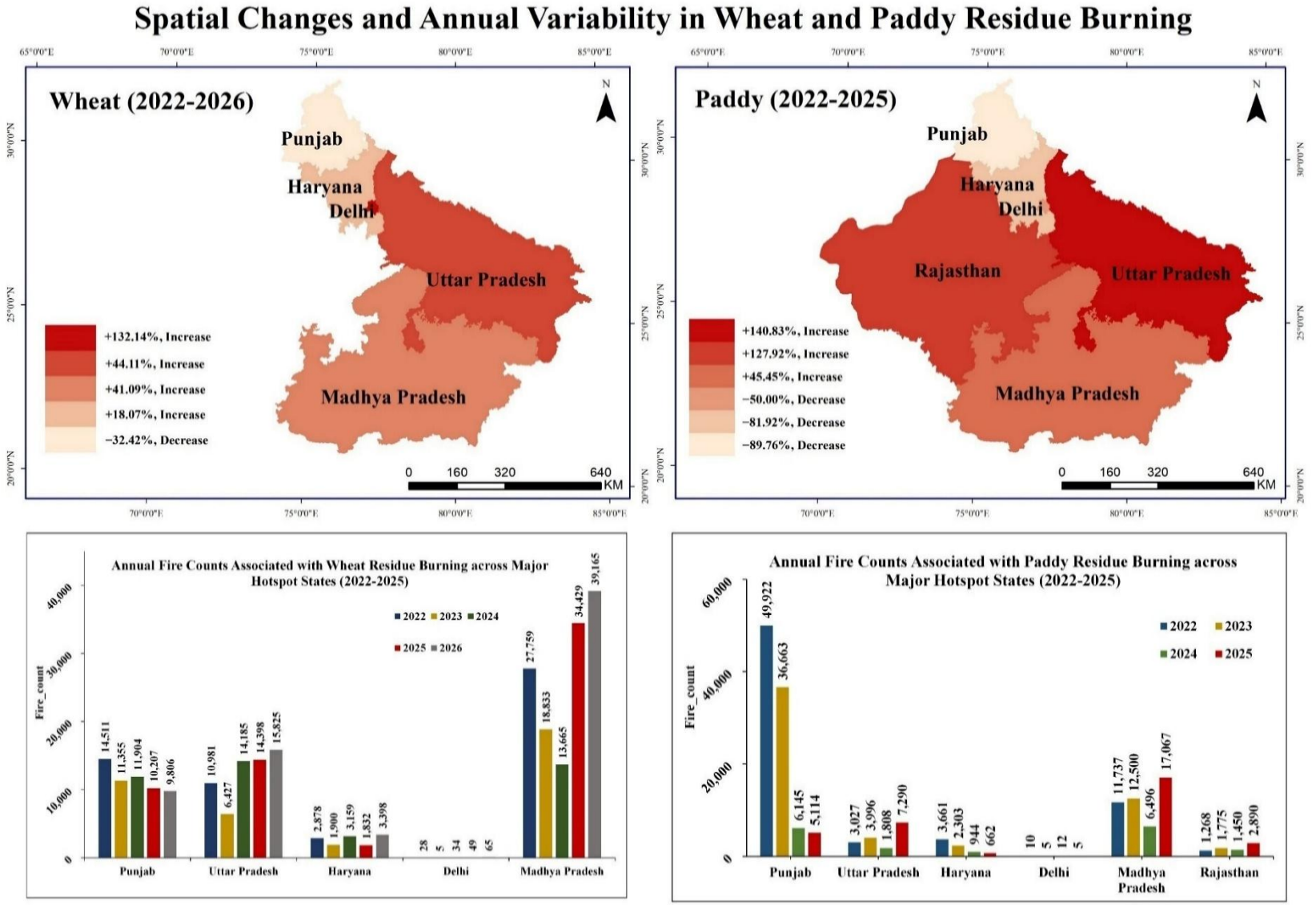

Figure 1c. The maps illustrate the change in the number of fire events detected by satellites between the first and last study years, and the graphs illustrate changes in the number of events of burning residue between years. [**Source:** ICAR-IARI-CREAMS]

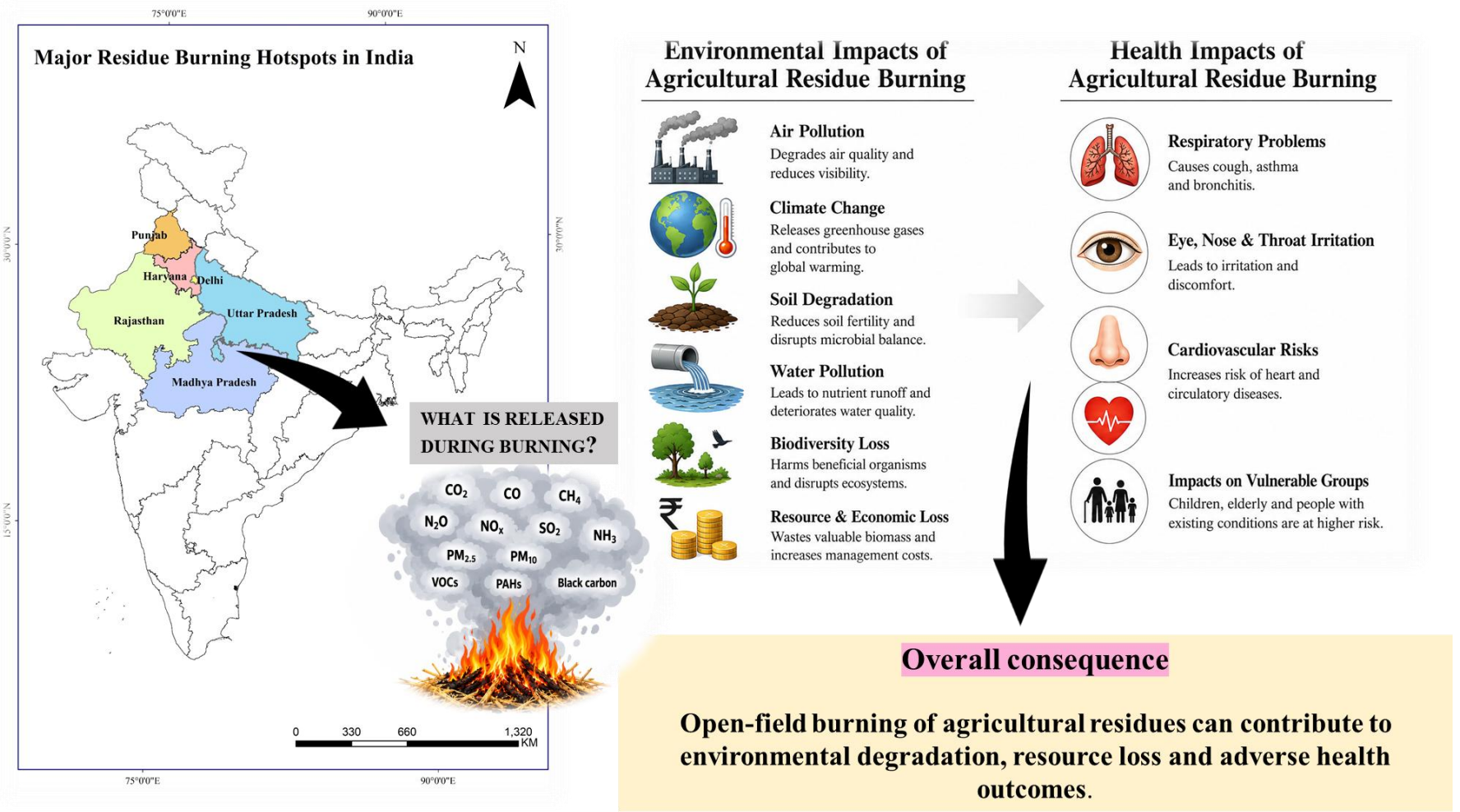

Figure 2. Environmental and health impacts of agricultural-residue burning. Major residue-burning hotspots, key emissions, and associated environmental and health impacts of open-field burning.

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3. The sustainable use of biochar

Thermochemical conversion of biomass in an oxygen-deficient environment produces biochar, a homogeneous solid rich in carbon [30]. It is a sustainable method of valuing agricultural waste that also enhances soil fertility, carbon sequestration, water purification, and waste management [31]. The circular economy's principles can be advanced by using biochar, which is derived from lignocellulosic wastes and turns waste into valuable products that reduce pollution in the environment and aid in climate regulation [32]. The main process for producing biochar, which has a porous structure, a primary carbon content, and environmental stability, is pyrolysis [33]. Its physicochemical properties allow it to be used in a variety of applications, including soil remediation, carbon storage, and pollutant adsorption; however, the feedstock and conversion process are complicated [34]. Pyrolysis is the main thermochemical conversion pathway that produces biochar, but added processes like hydrothermal carbonization, gasification, and torrefaction produce different carbonaceous or energy products and thus show different roles in the valorization of agricultural residues [35].

3.1. Methods of thermochemical conversion

Depending on temperature, oxygen content, and process strategy, biomass can be transmuted into biochar and other beneficial products by a variety of thermochemical processes, including hydrothermal carbonization, gasification, combustion, and pyrolysis [36]. Still, these procedures play dissimilar roles in the formation of biochar. The major process for making biochar is pyrolysis, while gasification generally creates syngas with char as a byproduct, torrefaction is largely employed as a moderate thermal pretreatment, and hydrothermal carbonization provides hydrochar. Since complete oxidation results in heat and ash rather than a recoverable biochar product, combustion is not taken into consideration further [37, 38]. Figure 3 shows the principal products of the main conversion pathways.

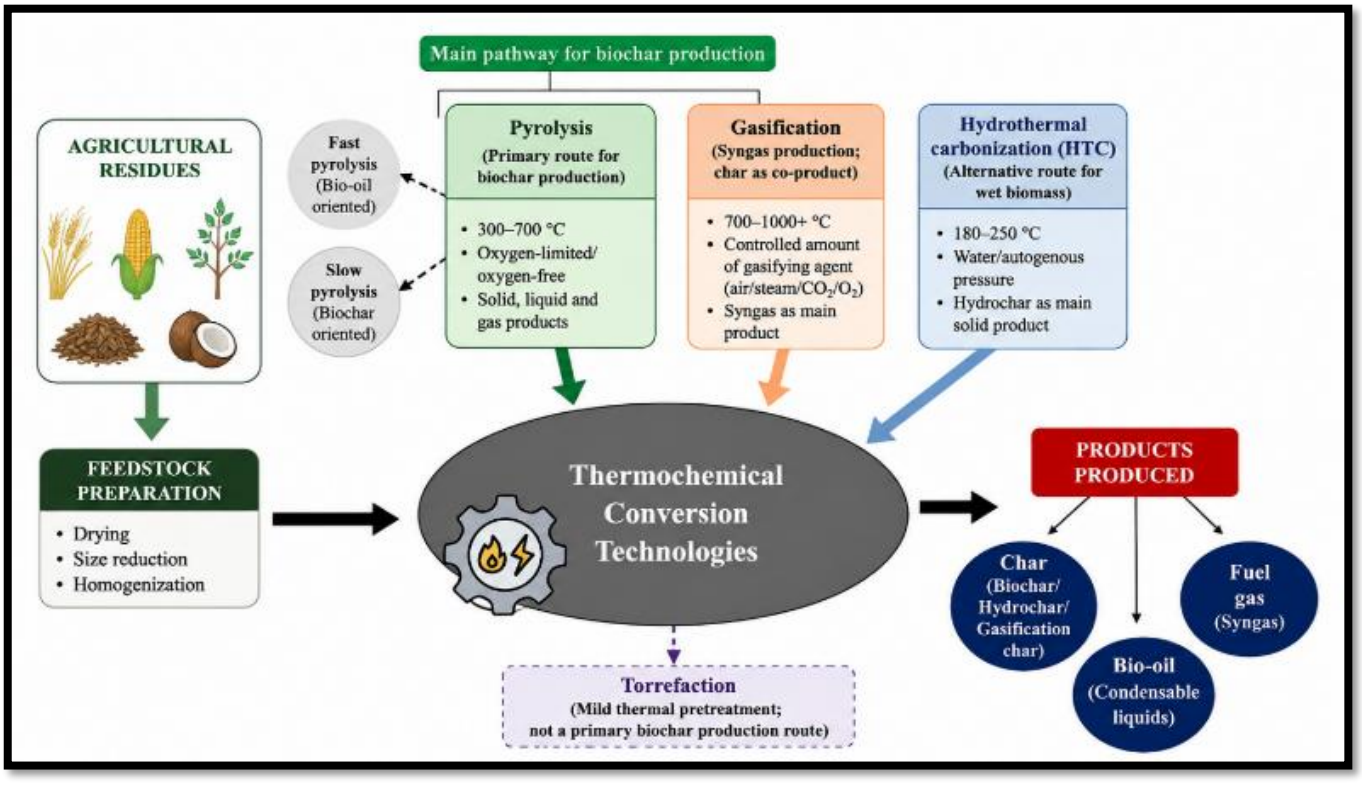

Figure 3. Thermochemical conversion pathways for agricultural residues and their principal products, highlighting pyrolysis as the principal route for biochar production.

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3.1.1. Carbonization via hydrothermal processes

In order to produce hydrochar and gaseous byproducts that satisfy the European solid fuel standard (EN 14961-6), hydrothermal carbonization (HTC) is carried out at 180–250°C using pressured hot water [38]. When compared to commercially available powdered activated carbon, a study using switchgrass-derived HTC biochar showed that KOH activation greatly increased porosity and adsorption efficiency for Cu^{2+} and Cd^{2+} removal [39]. Because wet biomass can be treated under hot compressed water without the considerable drying typically required for conventional dry pyrolysis, HTC is especially pertinent for agricultural leftovers with high moisture content [40] [55]. Because of the distinct reaction environment and carbonization methods, the resulting hydrochar is different from traditional pyrolysis-derived biochar [40]. Therefore, rather than being the primary method for producing traditional biochar, HTC is seen in this review as an alternate carbonization pathway for agricultural leftovers.

3.1.2. Gasification

At 800-1000°C, gasification transforms biomass into a flammable syngas mixture (mostly H_2 and CO) with little oxygen. Gasification is generally intended to maximize gaseous products rather than solid carbon, in contrast to pyrolysis. A lower percentage of char may still be present as a co-product; this material may be collected for use in environmental applications or additional treatment [41]. However, gasification is regarded in this research as a supplemental biomass-valorization approach rather than a primary biochar-production route since the high-temperature and partially oxidative conditions significantly diminish solid-carbon yield.

3.1.3. Pyrolysis

Due to its ability to manipulate variables like temperature, heating rate, and residence time, pyrolysis is the most researched and adaptable technique for producing biochar among these [34]. Biomass is broken down by pyrolysis (250–1000°C) in an oxygen-free environment, producing solid biochar, liquid bio-oil, and gaseous products. Process parameters determine product distribution; greater temperatures promote the generation of gas and oil but decrease charge yield [42, 43].

The three main product fractions produced by pyrolysis are biochar, bio-oil, and non-condensable gases, as shown in Figure 3. The relative amounts of these fractions are determined by the properties of the feedstock and the operating environment [44– 46]. Slow pyrolysis is classically preferred for biochar-oriented production due to its protracted residence time and relatively low heating rate, which favor the progress and retention of the solid carbon fraction [47].

Slow pyrolysis performed below 500°C with modest heating rates and long residence durations maximizes biochar synthesis by permitting secondary processes with recombination and repolymerization [48, 49]. Fast pyrolysis, which is primarily concerned with producing bio-oil rather than optimizing the production of biochar, uses rapid heating and short vapor residence times [50, 51]. Reactors such as fluidized beds, ablative reactors, and rotating-cone systems with fine feedstock and regulated moisture conditions are used for actual heat transmission and conversion [52]. Pyrolysis temperature is one of the primary factors influencing the yield and physicochemical properties of biochar. Increasing the temperature typically promotes carbonization and devolatilization, which reduces the amount of biochar produced but frequently increases structural ordering, aromaticity, and carbon stability [44–46]. On the other hand, biochar at lower temperatures might hold on to more volatile materials and functional groups that include oxygen. Biochar yield, carbon stability, surface functionality, and porosity are thereby traded off.

The content of the feedstock has a significant impact on the characteristics of biochar produced by pyrolysis. The cellulose, hemicellulose, lignin, ash, mineral, and extractive contents of agricultural residues vary, and these differences impact thermal breakdown, carbon yield, pH, ash content, surface chemistry, and adsorption behavior [27, 37, 49, 50]. As a result, variations in biochar cannot be attributed only to pyrolysis temperature; feedstock composition and the entire thermal history must also be taken into account.

Other pyrolysis and reactor parameters that can influence heat and mass transfer during pyrolysis and subsequently the properties of biochar are heating rate, reaction time, moisture content, particle size, and reactor architecture [37, 49–52]. Thus, the pyrolysis conditions for environmental uses need to be selected accordingly to the use of the biochar and not only

to maximize its yield. Biochar for pollutants may have to balance between porosity and reactivity of the surface with carbon storage, while carbon storage biochar may have to pay more attention to the stability of the carbon.

3.1.4. Elements affecting the yield and characteristics of biochar

The combination of feedstock parameters and thermochemical operating conditions determines the properties of biochar made from agricultural residues. Feedstock type, moisture content, particle size, pyrolysis temperature, heating rate, residence duration, reactor configuration, and process environment are all significant variables [37, 49–52].

Feedstock characteristics: The biochemical and mineral composition of agricultural residues, including rice husk, wheat straw, corn stover, sugarcane bagasse, coconut shells, nut shells, and other lignocellulosic wastes, varies significantly. This heterogeneity can result in large variations in biochar yield and ash content, pH, electrical conductivity, surface area, elemental composition, functional groups, and adsorption properties [53].

Pyrolysis temperature: An increase in temperature generally decreases the yield of biochar and increases the number of volatiles and carbonization that occur, while affecting the aromaticity and carbon stability [46, 47, 54]. Though some functional groups that include oxygen may also be reduced by intense heat treatment. Consequently, it is not always the case that greater temperatures result in biochar that is always better.

Heating rate and residence time: Whereas residence time impacts subsequent de-volatilization and secondary reactions, heating rate affects heat penetration and the relative influence of primary and secondary thermal reactions [48–50].

Particle size and moisture content: The moisture content influences the energy requirement and heat transfer behaviour of the process, and the particle size influences the thermal uniformity of the process. Proper drying of the feedstock and management of particle size can, therefore, improve the process repeatability and energy efficiency. Even if the nominal temperature is the same for all reactors, the use of different reactor configuration, such as fixed-bed, fluidized-bed, rotary kiln, auger, etc., can produce biochar with different characteristics due to the difference in mass and heat transfer conditions [49–52].

Overall, the process of biochar production does not seem to be a good deal between quality and quantity. Conditions that maximize solid production do not necessarily maximize surface area, porosity, adsorption capacity, and stability of carbon. However, there is a possibility of enhancement of stability and carbonization with strong heat treatment, but the yield and some surface functional groups may be reduced.

Table 1. Comparative overview of thermochemical conversion pathways relevant to agricultural-residue valorisation.

Process	Typical operating conditions	Main product	Solid carbon product	Main purpose	References
Slow pyrolysis	~300–600°C; low heating rate; longer residence time; oxygen-limited	Biochar + vapors + gases	High biochar fraction	Biochar and carbon production	[37,48,49,51]
Fast pyrolysis	~400–600°C; rapid heating; short vapor residence time	Bio-oil + gases + char	Low–moderate char fraction	Bio-oil production	[50–52]
Hydrothermal carbonization (HTC)	~180–250°C; hot compressed water; autogenous pressure	Hydrochar + aqueous products + gases	Hydrochar	Carbonization of wet biomass	[41,42]
Gasification	~700–1000°C; limited gasifying agent	Syngas + gases + char/ash	Low char fraction	Syngas/energy production	[41]

Note: Operating ranges are indicative and vary with feedstock composition, reactor configuration, heating rate, residence time, pressure, and process atmosphere.

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This trade-off will become especially critical when biochar is subsequently activated, as this will further change its surface chemistry, pore structure, and carbon production. Table 1 shows a comparison between different main thermochemical conversion processes, their operational characteristics, their main products, and their suitability for the production of biochar.

According to Table 1, when producing biochar is the main goal, slow pyrolysis is the most directly relevant pathway, while fast pyrolysis favors the production of bio-oil, HTC turns wet biomass into hydrochar, gasification mostly produces syngas, and torrefaction primarily serves as a biomass-upgrading process.

The final biochar has physicochemical properties that depend on the feedstock and the procedure, which dictate whether it is suitable for environmental applications and further activation. Therefore, as will be covered in the next section, thorough characterization is necessary to connect production conditions with biochar structure, surface chemistry, stability, porosity, and functional performance [55].

4. Biochar characterization

The characterization of biochar is a crucial process in defining whether biochar is suitable in the environment or in commerce or not [56]. It involves proximate, ultimate, physiochemical, surface, and structure analysis (Figure 4) [57]. Proximate analysis measures moisture, volatile matter, ash, and fixed carbon by an ordinary drying process in a muffle furnace [58]. Ultimate analysis determines the number of organic elements (C, H, O, N, S) using an elemental analyser and inorganic ash using inductively coupled plasma mass spectrometry (ICP-MS) [59]. Physiochemical analysis involves pH, electrical conductivity, and cation exchange capacity, which was determined through ICP, to determine the interaction of soil and retention of nutrients [60]. Mercury porosimeter, stereopycnometer, and nitrogen or CO_2 adsorption are used to determine such physical parameters as density, surface area, and pore volume [38, 60].

Surface characterization involves Boehm titration for surface acidity and functional group analysis through fourier-transform infrared (FTIR) and Raman Spectroscopy [61, 62]. Scanning electron microscope (SEM) reveals surface morphology, while SEM-EDX and X-ray photoelectron spectroscopy (XPS) determine elemental composition and surface chemistry [63–65]. Structural measurements make use of X-ray diffraction spectroscopy (XRD) to determine the crystalline phase and transmission electron microscopy (TEM) to see the nanostructure. Thermogravimetric analysis (TGA) is used to determine thermal stability, whereas synchrotron-based NEXAFS, EXAFS, and XANES methods will help reveal the composition of materials at the atomic level. The aromaticity and carbon stability are measured through the nuclear magnetic resonance (NMR) and raman spectroscopy [10, 66, 67]. This type of extensive analysis will help learn more about biochar behaviour in soil amendment, carbon sequestration, and pollutant adsorption.

4.1. Biochar activation

In order to improve the physicochemical characteristics of biochar and make it more suitable for environmental applications, activation is a crucial step that increases the material's surface area, porosity, surface reactivity, and abundance of functional groups [68–70]. The adsorption effectiveness of raw biochar toward environmental pollutants may be limited by its relatively limited pore accessibility and surface functioning, despite the fact that it is carbon-rich and generally stable [71, 72]. Activation creates accessible pore networks and application-specific surface chemistry by altering the carbon matrix by regulated physical, chemical, biological, or hybrid mechanisms [73]. As a result, activated biochar has shown improved removal of pesticides, antibiotics, dyes, heavy metals, and other organic and inorganic pollutants [74, 75]. Figure 5 summarizes the main activation mechanisms and the ensuing changes in the characteristics of biochar.

Although they both come from biomass, biochar and activated carbon are different carbonaceous compounds. While activated carbon goes through an extra activation stage to create a highly porous structure and improve surface reactivity, biochar is made by thermochemically converting biomass under oxygen-limited conditions, mostly by pyrolysis [76, 77]. An intermediate position is occupied by activated biochar, which is created by further modifying a biochar precursor through physical, chemical, or combination activation to customize its surface chemistry and pore structure [77].

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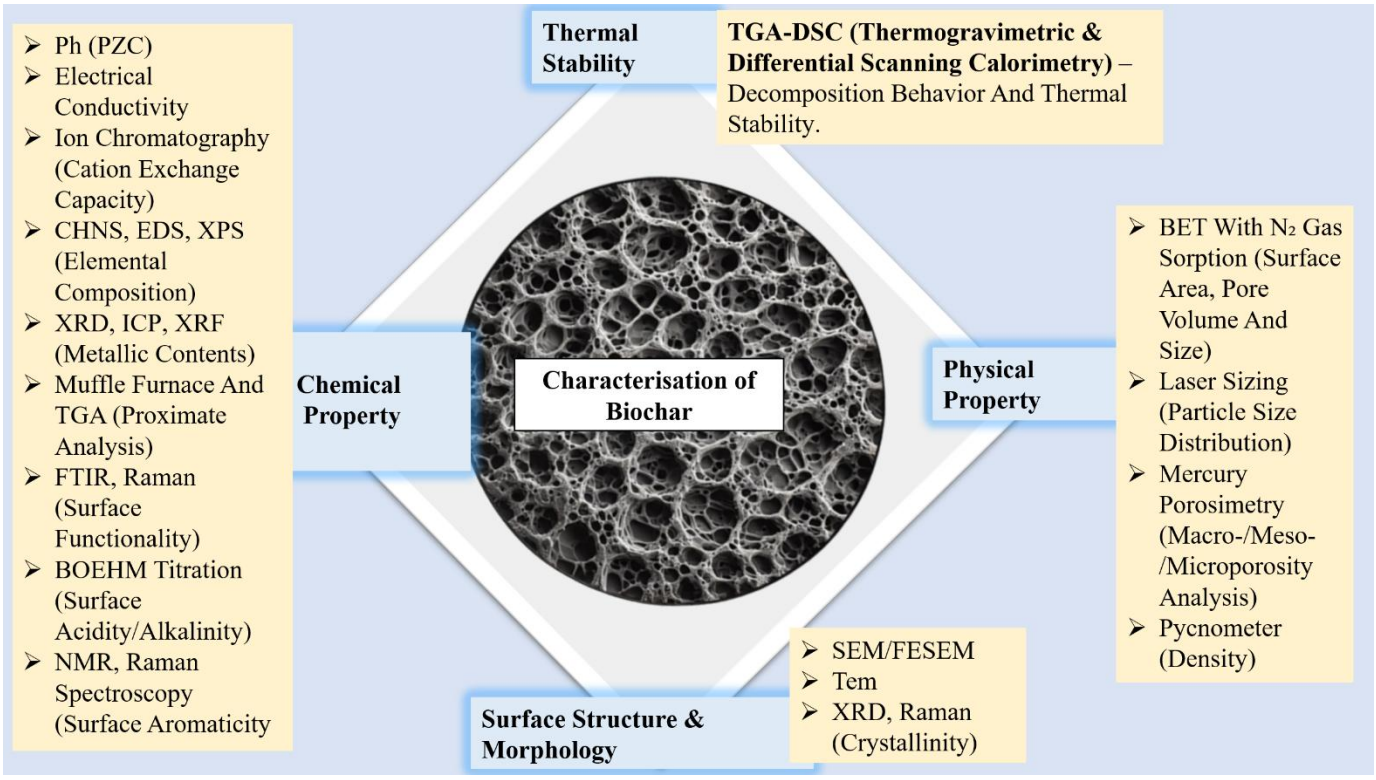

Figure 4. Classification of analytical techniques used for complete characterization of Biochar.

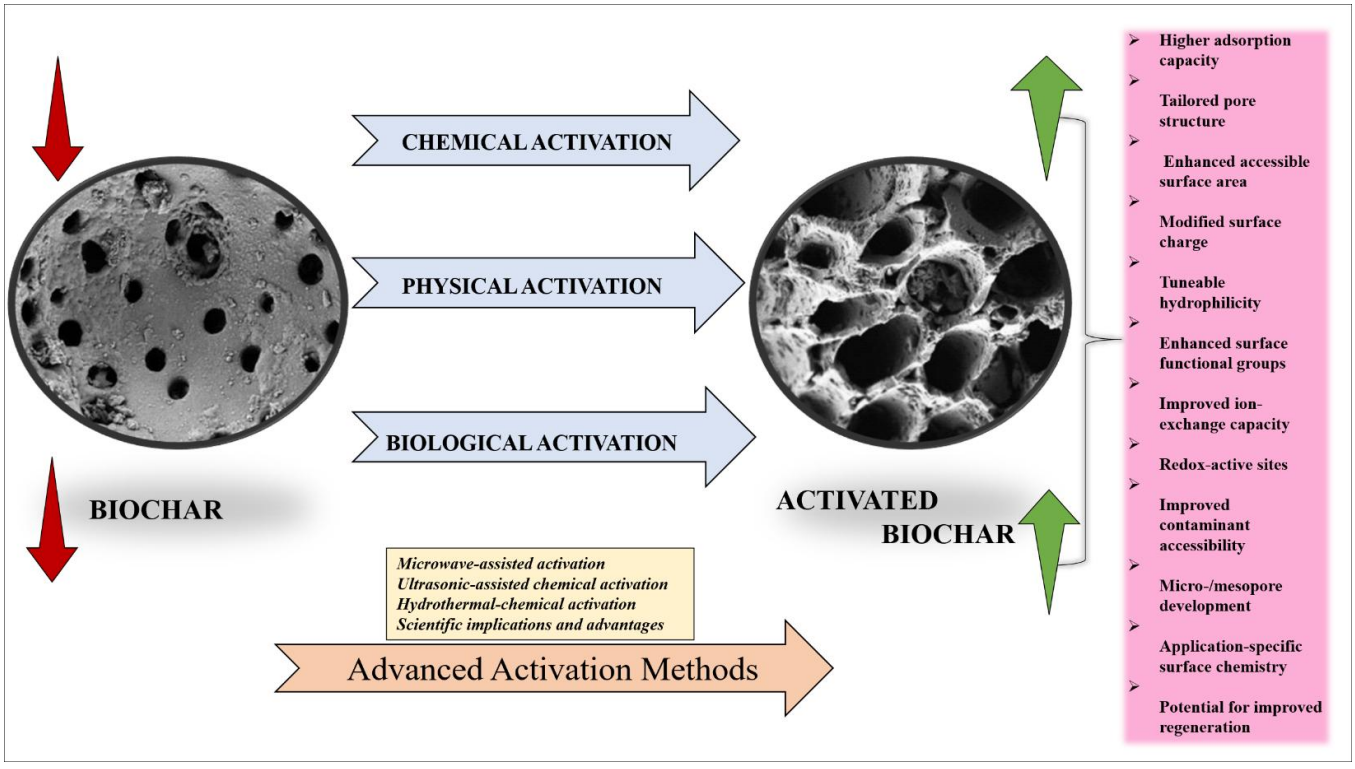

Figure 5. Activation strategies for enhancing the physicochemical and functional properties of biochar.

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Different physicochemical properties are the outcome of these several manufacturing routes. While activation can alter surface functional groups and charge and increase accessible surface area and pore volume, biochar typically maintains a heterogeneous pore structure, mineral fraction, and feedstock-dependent surface chemistry [77, 78]. Surface area alone, however, cannot account for adsorption performance; interactions with particular pollutants are governed by a combination of pore-size distribution, functional groups, mineral phases, and surface charge [78]. Due to extra heat or chemical treatment, activation may also lower carbon yield, resulting in a trade-off between material recovery and structural development [77].

Although biochar and activated carbon have similar uses, their characteristics and intended uses might be very different. While activated carbon is frequently designed for high-performance adsorption due to its highly developed pore structure and surface area, biochar is extensively researched for soil amendment, carbon management, and pollutant immobilization [76-77]. While maintaining the potential benefits of agricultural-residue valorization, activated biochar can offer improved adsorption and surface reactivity when compared to untreated biochar [76-78]. Therefore, rather than strictly separating their uses, the choice of biochar, activated biochar, or activated carbon should be based on the intended application, necessary material qualities, and processing requirements [79].

4.1.1. Activation in one and two steps

One-step or two-step methods are typically used to activate biochar, and each method offers varying levels of control over carbon structure, pore development, and surface chemistry. One-step activation lets carbonization and activation occur at the same time by impregnating biomass with an activating chemical and subjecting it to a single thermal treatment. This method can simplify processing, reduce the number of processing steps, and provide an energy-efficient route for the manufacture of activated carbonaceous materials [80]. In contrast, two-step activation includes an extra activation process following the first carbonization cycle. The carbonaceous matrix is formed during the first stage of thermal decomposition, which eliminates volatile components. The pore structure and surface functionality are further developed during the activation stage, which employs chemical or physical agents [81–83].

In two-step processing, the activation phase can contain chemical reagents like acids, bases, and specific salts or oxidizing gasses like steam and CO_2 [84, 85]. While two-step methods permit more control over the structural and chemical properties of the final activated biochar, one-step methods offer operational simplicity and can lower processing requirements [86, 87]. Microporous and mesoporous materials are especially well-suited for chemical activation [88].

For instance, lettuce-waste biochar with a reported Cd^{2+} adsorption capacity of 196 $mg.g^{-1}$ within 30 minutes was created by one-step hydrothermal carbonization using H_3PO_4 at about 200°C.

Surface complexation, ion exchange, and electrostatic attraction all contributed to the adsorption process [89]. Similarly, due to modifications in surface chemistry, rice-husk biochar treated with HCl and NaOH showed enhanced Cd^{2+} adsorption [90]

4.1.2. Physical activation

Physical activation generally involves oxidizing gases, particularly steam and CO_2, to develop the pore structure and enhance the accessible surface area of biochar. During activation, the gas combines with the carbon matrix and eliminates volatile and less-ordered carbon fractions, eventually opening and increasing holes [111]. Steam activation has been proven to increase the sorption of Cu^{2+}, Zn^{2+}, and Cd^{2+}, while also eliminating tar-like compounds and exposing previously inaccessible interior surfaces [112]. Steam treatment of Miscanthus-derived biochar increased aromaticity and surface area; however, alterations in oxygen-containing functional groups may vary according to the activation circumstances [113]. A meta-analysis found a significant improvement in heavy-metal adsorption subsequent to physical activation, emphasizing the importance of pore volume and specific surface area in inducing adsorption effectiveness [114]. Steam activation proceeds through gas-solid reactions, primarily the water-gas reaction, $C + H_2O \rightarrow CO + H_2$ ($\Delta H \approx +117$ $kJ.mol^{-1}$), followed by the water–gas shift reaction, $CO + H_2O \rightleftharpoons CO_2 + H_2$ ($\Delta H \approx -41$ $kJ.mol^{-1}$) [115]. These reactions progressively remove reactive carbon and volatile carbonaceous species, generating new micropores and widening existing pores, thereby

increasing the accessible surface area and pore volume [116, 117]. BET surface area has been reported to be as high as 793 $m^2.g^{-1}$ in different biochar and as low as 136 $m^2.g^{-1}$ in various feedstocks in steam activation [118]. For instance, tea-waste biochar showed a rise from 342.2 to 576.1 $m^2.g^{-1}$ after activation [119], and the best activation conditions have led to surface areas > 1000 $m^2.g^{-1}$. The latter could lead to over-activation, leading to an excessive burn-off and potentially to a widening or collapse of pores, however, which requires careful control of temperature, residence time, and the ratio of oxidant to biochar [120, 121].

Physical contact may also change the distribution of functional groups and surface polarity. The steam treatment can lead to changes in the hydroxyl groups and the surface polarity and reduce the hydrophobicity [122]. The pyrolysis and activation temperatures could also be increased, which could further modify the biochar pH and surface charge, thereby altering the electrostatic interaction with ionic contaminants [123, 124]. The BET examination usually suggests that micro- and mesoporous structures have formed, followed by roughened surfaces and surface breakage observed by SEM and TEM that are linked to the presence of the pores [125, 126].

Table 2. Representative examples of physical, chemical, biological, and advanced activation strategies for biochar and their reported effects.

S. No.	Activation route	Raw material	Activating agent / process	Activation conditions	Major effect / outcome	Reference
1	**Chemical**	Corn straw	KOH	Two-step pyrolysis + KOH activation	BET surface area 2183.8 $m^2.g^{-1}$; highly developed micropores; enhanced Cr(VI) and naphthalene adsorption	[91]
2		Rice husk residue	H_3PO_4	500°C, 1 h	BET surface area 1016 $m^2.g^{-1}$; increased micro-/mesoporosity	[92]
3		Rice husk	H_3PO_4	500°C, 0.5 h	High surface area; pore development strongly influenced by H_3PO_4 concentration and washing	[93]
4		Hickory wood	NaOH	Pyrolysis followed by NaOH modification	Increased surface area and CEC; 2.6–5.8× higher heavy-metal adsorption than pristine biochar	[94]
5		Olive stones	KOH	Carbonization at 840°C followed by KOH activation	Strongly developed microporosity and high surface area	[95]
6		Almond, coconut, oil-palm, pistachio and walnut shells	K_2CO_3	Optimum around 1073 K (~800°C)	High specific surface area; K_2CO_3 effectively developed pore volume	[96]
7		Pine sawdust	$ZnCl_2$	600°C carbonization + 850°C activation	Developed porous activated carbon; improved adsorption characteristics	[97]
8		Hickory-chip biochar	H_2O_2	Oxidative modification	Increased oxygen-containing functional groups and enhanced methylene-blue adsorption	[98]

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Table 2. (Continued).

9		Olive stone char	Steam	800–850°C	Increased pore volume and development of micro-/mesoporosity	[99]
10		Pine/spruce/fir biochar	Steam	900°C; 60 min	BET surface area increased from 50 to 1025 $m^2.g^{-1}$	[100]
11		Spent mushroom substrate	Steam	Steam activation of biochar produced at 450 °C	BET 332 $m^2.g^{-1}$; pore volume 0.29 $cm^3.g^{-1}$; crystal-violet adsorption increased from 255 to 1057 $mg.g^{-1}$	[101]
12		Invasive plant (*Sicyos angulatus*)	Steam	700°C	Steam activation strongly enhanced sulfamethazine sorption; 700°C activated biochar showed the highest sorption	[102]
13		Tea waste	Steam	700°C	BET increased from 342.2 to 576.1 $m^2.g^{-1}$; pore volume increased from 0.022 to 0.109 $cm^3.g^{-1}$	[103]
14	**Physical**	Mixed conifer mill residues	Steam	816–927°C; 45–60 min	Surface areas increased to 744.8–1092.9 $m^2.g^{-1}$, depending on biochar precursor	[104]
15		Wood waste	Steam	Pyrolysis followed by steam activation; 850°C pyrolysis condition gave strong mesopore development	Steam activation enhanced pore structure; 850°C steam-activated biochar showed highest mesopore formation	[105]
16		Olive stone	CO_2	650–950°C	CO_2 activation progressively developed micropores and mesopores and increased surface area	[106]
17		Food-industry waste biochars	CO_2 / CO_2–steam	Gas-phase activation	CO_2–steam increased porosity and reactivity; CO_2 activation stabilized mineral phases and affected heavy-metal adsorption	[107]
18		Jute sticks	Pressurized CO_2	Carbonization under N_2 followed by pressurized CO_2 activation	Developed micro-/ultramicroporosity and improved CO_2-capture performance	[108]
19	**Advanced / assisted**	Waste palm shell	Microwave + steam	550–600°C; ~5 min	Steam activation gave 527.4 $m^2.g^{-1}$; combined physicochemical activation reached 717.8 $m^2.g^{-1}$	[109]
20		Softwood biochar	Ultrasound + NaOH	Ultrasonic pretreatment followed by NaOH activation	Enhanced accessibility/activation and improved heavy-metal removal	[110]

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4.1.3. Chemical activation

Chemical activation is the process of treating the biomass or prepared biochar with chemical activating agents, typically acids, alkalis, oxidants, or selected salts. This method works best for the concomitant growth of porosity and alteration of surface chemistry [95, 115]. Acidic agents such as H_3PO_4, HNO_3, and H_2SO_4 can stimulate pore growth and boost oxygen-containing surface functions, whereas alkaline agents such as KOH, NaOH, and Na_2CO_3 are particularly effective in producing micropores and changing basic surface sites [95]. Acids like H_3PO_4, HNO_3, and H_2SO_4 can promote pore formation and enhance the oxygen-containing surface functions, while alkaline agents (KOH, NaOH, and Na_2CO_3) can form micropores and modify the basic surface sites. Acid treatment using HCl, H_2SO_4, H_3PO_4, or citric acid may increase the polarity of the surface and add or expose functional groups like –OH and –COOH [127]. H_3PO_4-modified biochar has been reported to obtain a specific surface area of 1627 $m^2.g^{-1}$ compared with 411 $m^2.g^{-1}$ for untreated biochar [128]. Similarly, $KMnO_4$ alteration has boosted the metal-adsorption capacity of walnut-derived biochar. Alkaline activation with KOH, NaOH, and Na_2CO_3 stimulates micropore growth and the creation of basic surface sites. KOH-treated bamboo biochar, for example, achieved a surface area of roughly 1555 $m^2.g^{-1}$ and displayed better Cr removal, whereas NaOH-treated biochar showed substantially improved metal adsorption [114]. Combined acid–alkali treatments can further change pore shape and surface chemistry, leading to increased pollutant removal [129].

Chemical activation may also modify the elemental composition and the electrical characteristics of biochar by modifying the H/C and O/C ratios and increasing the relative degree of carbonization and aromaticity. These changes may affect the thermo-stability and electron-transfer properties. The surface chemistry change after activation is often suggested by spectroscopic characterization. FTIR can provide information on changes in the O–H and C=O bands, while XPS can provide information on changes in oxygenated carbon species and heteroatom-containing functionalities [130, 131]. Information on structural ordering and graphitic growth can also be obtained by XRD and Raman spectroscopy [132].

The success of chemical activation varies greatly depending on the activating-agent type, impregnation ratio, activation temperature, residence period, washing technique, and feedstock composition. Therefore, chemical activation should be seen not merely as a strategy for increasing surface area but as a means of modifying pore architecture and surface chemistry for specific pollutants [133]. KOH activation is particularly effective for producing highly accessible microporosity through alkaline etching of the carbon matrix [134]. On the other hand, high KOH input or harsh activation conditions may reduce biochar output and increase carbon burn-off [135]. Although NaOH uses a similar alkaline activation route, the resultant surface chemistry and pore shape can vary depending on the activation circumstances and feedstock [136]. H_3PO_4 adds surface functions containing phosphorus and enhances dehydration, cross-linking, and pore development [137]. Although using Zn-containing activating agents necessitates consideration of residual metals and post-treatment/washing requirements, $ZnCl_2$ improves pore formation. [138]. Fe-based activation can generate iron-containing phases that provide additional adsorption and redox-active sites [139], while H_2O_2 and $KMnO_4$ provide oxidative surface modification and increase oxygen-containing functional groups [140]. Organic-acid treatment represents a comparatively mild approach for surface functionalization and demineralization, particularly through enrichment of acidic functional groups [141].

4.1.4. Biological activation

Biological activation is the alteration of biochar utilizing microbes, bacteria, fungi, or enzymes to improve surface reactivity and functional-group density [167–169]. Unlike conventional chemical activation, biological modification predominantly occurs through biological interactions that affect surface functionality, acidity, and contaminant-binding properties. Biochar derived from digested corn-straw silage has exhibited considerable Cd^{2+} elimination following biological treatment [167]. Phosphate-solubilizing bacteria have also increased Pb^{2+} adsorption by rice-husk and pig-manure biochar, while yeast-modified maize-straw biochar has exhibited better Cd^{2+} adsorption [168-170].

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Table 3. Comparative characteristics of major chemical activating agents used for biochar.

Activating agent	Principal effect	Pore development	Surface functionality	Major environmental concern	Washing requirement	Relative scalability	References
KOH	Strong alkaline etching of carbon matrix	High microporosity; hierarchical pores possible	Oxygen-containing and basic surface sites	High chemical consumption and corrosivity	Extensive washing generally required	Moderate	[142–145]
NaOH	Alkaline carbon etching and pore opening	Micro-/mesopore development	Oxygen-containing surface groups	Corrosivity and alkaline wastewater	Washing required	Moderate–high	[146–148]
H_3PO_4	Dehydration, cross-linking and pore development	Micro- and mesoporosity	Phosphate- and oxygen-containing groups	Phosphate-containing wastewater and residual P	Washing required	High potential	[149– 152]
$ZnCl_2$	Dehydration and inhibition of tar formation	Strong microporosity	Modified oxygenated surface chemistry	Zn residues, corrosion, and wastewater	Recovery/washing important	Moderate	[153–155]
Fe salts	Mineral loading and surface modification	Moderate; feedstock dependent	Fe–O/Fe-containing phases	Residual metal and secondary waste	Washing may be required	Moderate	[156–158]
H_2O_2	Oxidative surface modification	Usually secondary to surface functionalization	–OH, C=O and –COOH groups	Oxidant consumption and process-safety requirements	Generally lower residual-inorganic burden	Moderate–high	[159,160]
$KMnO_4$	Oxidation and Mn-oxide formation	Variable	Oxygen groups and Mn-oxide phases	Mn-containing residues	Washing required	Moderate	[161, 162]
Organic acids	Mild demineralization and surface functionalization	Generally limited pore etching	Mainly –COOH and other O-containing groups	Generally lower chemical hazard, but process-dependent	Generally lower inorganic-residue burden	Promising	[163–166]

Biological alteration can boost ion-exchange activities and increase the availability or accessibility of oxygen-containing functional groups, particularly -OH and -COOH, hence facilitating complexation with metal ions [171]. Surface-charge studies reveal that biological alteration can diminish the point of zero charge and enhance surface acidity through the creation or exposure of carboxyl, hydroxyl, and carbonyl groups. Such modifications can increase interactions with positively charged metal ions and nutritional species.

Compared with typical chemical activation, biological techniques provide options for surface modification under comparably moderate circumstances and may lessen the need for corrosive chemical reagents. However, their performance depends greatly on the microbial system, incubation conditions, feedstock properties, treatment duration, and target pollutant. Therefore, biological activation should be seen as a complementing and evolving activation approach rather than being treated as equivalent to conventional high-temperature chemical activation [172].

4.2. Advanced and hybrid activation methods

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The biochar technology has been continuously advanced in the past years, and several combined activation methods have emerged, which combine physical, chemical, biological, or energy-assisted activation to achieve a more controlled pore structure and surface chemistry than the traditional biochar preparation methods. Other approaches to enhancing the activation efficiency, shortening the processing time, and altering the surface properties are microwave-assisted, ultrasonic-assisted, and hydrothermal-chemical methods [173, 174]. Such strategies may help to change the adsorption capacity, pore structure, distribution of functional groups, adsorption kinetics, and regeneration potential and offer opportunities for improvement in the process efficiency.

4.2.1. Microwave-assisted activation

Microwave-assisted activation is a proper way to transfer energy quickly and volume-wise into the precursor or biochar matrix through dielectric heating. Microwave irradiation can create pores, devolatilize, and heat rapidly, as well as decrease the activation time and even energy cost when compared to the conventional external heating. [172, 175, 176].

The method can encourage the growth of micro- and mesopores and increase surface heterogeneity. Microwave-activated biochar has shown BET surface areas surpassing 1000 $m^2.g^{-1}$ in some systems and has shown increased adsorption capability toward heavy metals and pharmaceutical pollutants [177]. Microwave–hydrothermal hybrid treatment has also been shown to improve processing time while retaining carbon yield and structural integrity [178]. Structural analysis further reveals that microwave treatment can impact carbon ordering and pore homogeneity. XRD and Raman investigations have been utilized to identify changes in graphitic ordering, while SEM observations reveal the creation of more uniformly distributed micro- and mesopores [179]. Therefore, microwave-assisted activation is a capable way for rapid and energy-conscious engineering of activated biochar.

4.2.2. Ultrasonic-assisted chemical activation

Ultrasonic-assisted activation uses acoustic cavitation to increase the interaction between activating chemicals and the carbonaceous matrix. The development and burst of small bubbles cause restricted physical effects that can surge the penetration and distribution of chemical activators such as KOH and H_3PO_4 within biomass or biochar structures [180–182].

This process can enable de-ashing, micro-crack creation, and greater availability to interior surfaces, providing interconnected pore networks and improved oxygen-containing surface functions. Ultrasonic treatment has been linked with improved adsorption of both inorganic and organic pollutants [183]. Ultrasonic-KOH activation of rice-husk biochar has been shown to increase Cu^{2+} adsorption relative to old chemical activation, primarily because of increased exposure of active sites and better surface heterogeneity [184–186].

FTIR and XPS investigations specify changes in O-H, C=O, and C-O functionalities following ultrasonic activation, indicating improved oxygen functionalization and surface reactivity. The blend of chemical activation with ultrasound consequently provides a path for enhancing activating-agent convenience while perhaps declining the severity or length of conventional treatment [187, 188].

4.2.3. Hydrothermal-chemical activation

Hydrothermal-chemical activation integrates hydrothermal carbonization (HTC) with the following or immediate chemical modification. HTC usually happens in water at around 180–250°C at autogenous pressure, letting wet biomass to be processed deprived of substantial drying. During hydrothermal treatment, the breakdown and reorganization of cellulose and hemicellulose lead to the formation of a carbon-rich structure [189, 190].

Subsequent chemical treatment employing agents such as KOH, H_3PO_4, or H_2O_2 can supplementarily enhance pore architectures and introduce or expose oxygen-containing functions such as –OH and –COOH. Thus, the joint process can contribute to control over pore expansion while increasing hydrophilicity, ion-exchange capacity, and redox activity. These characteristics are especially crucial for the removal of organic and heavy-metal contaminants. [191, 192].

Current discoveries validate that hydrothermal–KOH activation of bagasse- and rice-husk-derived biochar can produce surface areas above 1200 $m^2.g^{-1}$ while keeping carbon yields above 60%, with substantial adsorption performance toward Pb^{2+} and Cr (VI) [193, 194]. SEM and TEM measurements determine substantial pore formation and rather regular pore networks, while BET and FTIR investigations show increased surface area and oxygen-containing functional groups [195, 196].

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Review Article

5. Scientific implications and advantages

Additionally, the combination of the physical and chemical characteristics and the more sophisticated energy-assisted techniques provides further flexibility for engineering biochar for an environmental application. Hybrid activation can enhance surface area, pore accessibility, functional-group diversity, adsorption speed, and regeneration ability but can also offer some ability to reduce the amount of heat degradation and carbon loss [197].

Advanced activation methods may also facilitate heteroatom insertion, such as N-, P- and S-containing functions, that could change the electron-donating properties and redox activity. Hybrid techniques can be less time-consuming than standard activation and depending on the system, can reduce chemical usage and improve the valorisation of agricultural waste [198]. Therefore, comprehensive characterization using BET, Raman spectroscopy, and FTIR is required to obtain correlations between the activation conditions, the pore structure, the surface chemistry, and the functional performance [199].

Importantly, it is not the maximization of the BET surface area that should determine the best activation method. An optimal activation performance should be considered through the following parameters: Pore size distribution, accessible surface area, surface functionality, surface charge, adsorption capacity, regeneration potential, carbon yield, chemical consumption, energy demand, generation of wastewater, residual chemical risk, and scalability. In the case of agricultural residue-based biochar, this application-specific approach is particularly crucial because the feedstocks might range greatly in their chemical composition, which can lead to variable activation properties and, consequently, various physicochemical qualities [200, 201]. Given the circumstances, the shift in biochar engineering from traditional physical and chemical activation to biological, sophisticated, and hybrid methods is noteworthy. In addition to improving process efficiency, pollutant removal efficiency, and resource valorisation, the methods indicate possibilities for producing application-specific activated biochar from agricultural leftovers. [202].

Biochar is characterized by its wide surface area, porosity, and lateral abundance of reactive sites. It can be formed by combining chemical and physical activation [203, 204]. Because of these characteristics, it can be utilized in a variety of environmental and energy-related fields, including energy storage, wastewater treatment, soil restoration, and air purification (Figure 6) [205, 206]. Because of its adjustable surface chemistry, shape, and pore structure, which enable efficient adsorption catalysis and ion exchange, activated biochar is a sustainable alternative for environmental management.

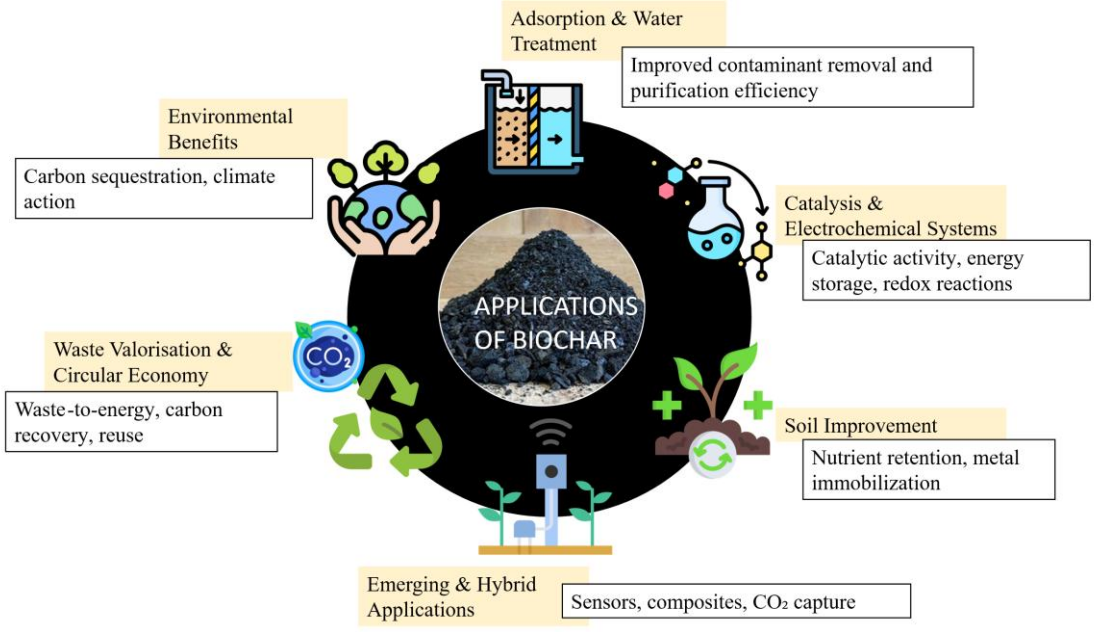

Figure 6. Activated biochar as a multi-purpose remediation agent in environmental sustainability.

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5.1. Removal of pollutants from water

Because of its limited surface heterogeneity, the non-activated biochar indicates a poor capacity for adsorption of organic contaminants, nutrients, and volatile organic compounds. When it came to volatile organic compounds, neem biochar was a great adsorbent; nevertheless, it was less effective when it came to heavy metals [207]. However, because of its micro- and mesoporous structure, activated biochar is better at removing a wide range of contaminants, including medications, dyes, heavy metals, and nutrients. [208, 209]. As an example, the phosphate adsorption efficiencies of the KOH-activated biochar-driven spent coffee grounds were 17.3, and the non-activated forms stood at 5.7% [210]. In a similar vein, the Fe-activated biochar has been reported to clean 90% of ibuprofen and carbamazepine in water, which is better than non-activated agro-waste biochar [211]. In addition, activation enhances surface redox processes. The catalytic efficiency of activated biochar in converting H_2O_2 improves the ability to decompose organic micropollutants, therefore mediating adsorption and catalysis [212].

The removal of pollutants by activated biochar involves numerous interacting pathways, and their proportional contribution depends on contaminant chemistry, surface functioning, pore structure, and solution parameters such as pH and ionic strength [213, 214]. For metal ions, ion exchange and surface complexation can occur through interactions with oxygen-containing functional groups, whereas electrostatic attraction is regulated by the surface charge of biochar and the ionic form of the contaminant [212, 213]. Mineral components may additionally facilitate precipitation of dissolved metals or phosphate under suitable chemical circumstances [215]. For organic pollutants, pore filling is encouraged by the generated micro- and mesoporous structure, whereas hydrogen bonding, hydrophobic interactions, and π–π interactions can contribute to the retention of polar and aromatic compounds [213, 215]. Therefore, the superior activity of activated biochar cannot only be attributed to the increase in surface area but is also due to the change in the accessibility of pores and the change in surface functional groups and surface charge, as well as the change in surface mineral phases. [213, 215].

Cadmium, lead, and copper ions (Cd^{2+}, Pb^{2+}, and Cu^{2+}) are effortlessly absorbed at low concentration, and are more low-cost and regenerable than standard sorbents [216, 217]. The addition of CaO and MgO is used as a supplement to the reaction to form hydroxyapatite ($Ca_5(PO_4)_3OH$) via the precipitation process. Colours (e.g., methylene blue, Congo red) are also removed by activated biochar through electrostatic π–π interactions [218, 219] and antibiotics such as tetracycline by hydrogen bonding and electron donor-acceptor interactions. These mechanisms can operate simultaneously but can have different levels of importance depending on the characteristics of the biochar, the activation conditions, the nature of the contaminant, and the water chemistry. [212, 213]. Mechanistic understanding therefore requires data from complementary inquiries such as FTIR or XPS, changes in surface charge, elemental composition, pore features, and contaminant speciation before and after adsorption [213, 215]. Such collaborative adsorption mechanisms make it an eco-friendly and inexpensive substitute to typical wastewater treatment methods [220].

5.1.1. Emerging contaminants

Pharmaceuticals and Per- and Polyfluoroalkyl Substances (PFAS) have a high adsorption rate on activated biochar due to hydrogen bonding, Electron Donor-Acceptor (EDA) interaction, and hydrophobic interactions. HPO_4 activated biochar adsorbed more than 300 mg/g of tetracycline through π-π interactions, whereas $ZnCl_2$-modified litchi seed biochar had more than 95% of Perfluorooctane Sulfonate (PFOS) and PFOA removed [221]. Perfluorobutanoic Acid (PFBA) and Perfluorooctanoic Acid (PFOA) biochar were also removed by Fe-impregnated graphitised biochar through pore entrapment and electrostatic forces [222]. Equally, biochar consisting of NaOH-activated lucerne hay achieved adsorption of 302 mg/g tetracycline adsorption, which proved the usefulness of alkaline activation in pharmaceutical removal. This data proves that CO_2/steam and acid/alkali treatment (H_3PO_4, KOH, H_2SO_4) is one of the activation approaches that can increase the efficiency of multifunctional pollutant removal [223].

5.2. Catalysis and electrochemical energy systems

One of the distinctions that characterize the two forms is thus the catalytic activity. Non-activated biochar is a catalyst support that contains few active sites and have an appropriate

catalytic effect in simple oxidation and reduction reactions. As an illustration, the non-activated biochar made of the waste products of agriculture can be used to support the low temperature oxidation of iron or cobalt catalysts but with mediocre performance [224]. On the other hand, activated biochar is a strong heterogeneous catalyst because it has a great specific surface area and contains large numbers of oxygenated functional groups. KOH- and H_3PO_4-activated biochar have much higher electron transfer abilities and are useful in catalytic ozone, photocatalysis, and fuel cell electrodes [225]. An example of such materials is polyacrylonitrile-activated biochar-laccase composites that have been used in bio-electrochemical reactors and enzymatic fuel cells to degrade pollutants and produce power efficiently [226]. Activated biochar also exhibits better electrochemical storage -chemically activated biochar electrodes have specific capacitances of more than 200 F/g, whereas non-activated electrodes have specific capacitance of less than 100 F/g [227]. Such performance is enabled by high conductivity and hierarchical porosity, which are attained by activation processes.

5.3. Soil amendment and agricultural remediation

In farms, non-activated biochar can be used to enhance the soil fertility by increasing the cation exchange capacity, moisture retention, and microbial activity. It has been mostly applied as a long-term soil amendment and carbon sequestration tool due to its high stability [166]. Nonetheless, activated biochar has the effect of improving the control of bioavailability of nutrients and pollutants. It has been demonstrated that acid-activated biochar can reduce ammonia (NH_3) emissions from manure storage by 37–51% during the first month, while the reduction over four months of storage was 25–28% [228]. Activated biochar metal doped is also used to facilitate soil detoxification. As an example, Pb^{2+} and Cd^{2+} immobilization by iron-modified biochar is more effective than the inactive analogue, which is explicated by better surface charge and redox potential [229].

5.4. Waste valorisation and circular economy applications

Non-activated biochar is a cost-effective, scalable waste valorisation strategy, transforming biomass residues into carbon sequestration products. It finds wide application in the stabilisation of municipal and agricultural waste but cannot react to complex pollutants [230]. On the other hand, activated biochar has a higher economic and functional value, as it can be used as a co-adsorbent or catalyst in waste-to-energy. Activation also improves adoption of toxins and facilitates their reuse in catalytic pyrolysis and biofuel production systems [231].

5.5. Emerging and hybrid applications

In other applications beyond the classical environmental applications, biochar, particularly in its highly activated form, is being advanced in biomedicines, sensors, CO_2 capture, gas storage, and composite materials. Carbon materials that are produced as biochar are currently employed in electrochemical detectors to measure trace metals ($Pb^{2+,}$ Cd^{2+}) with great sensitivity, compared to non-activated counterparts [232]. Mechanical strength and stability of food packaging and biomedical instruments Biodegradable polymers like polylactic acid (PLA) is made stronger and more stable by using biochar as a conductive filler [233]. Additionally, activated biochar has potential in CO_2 adsorption and hydrogen storage, in which its microporosity and surface functionalization are better than conventional activated carbons [234].

6. Recent advances in biochar activation strategies

Recent improvements in biochar activation have evolved from simply optimizing surface area toward application-specific control of pore shape, surface chemistry, and contaminant selectivity. Green modification techniques, including the use of less hazardous chemicals and alternate activation procedures, are increasingly being researched to lower the chemical intensity and environmental load associated with conventional activation [235, 236]. Recent comparative studies reveal that the activation approach greatly affects pore growth, surface functionality, and adsorption effectiveness, stressing the need to select activation conditions according to the target contaminant rather than optimizing surface area alone [237].

A significant strategy to enhance the recovery and reuse of activated biochar is magnetic manipulation. The addition of magnetic phases, especially magnetic iron compounds, can aid separation from treated water by applying an external

magnetic field and also create extra reactive sites [238, 239]. Magnetic biochar application in removing antibiotics is confirmed by recent research, which also highlights the challenges of material preparation, regeneration, secondary pollution, and manufacturing costs for potential applications [238]. Advancing surface engineering towards more selective and multifunctional biochar. Modification of surface charge, functional groups, electron-transfer properties, and contaminant affinity can be achieved by chemical oxidation, heteroatom modification, and insertion of functional mineral or metal phases [236, 240]. Recent studies on organic pollutants and heavy metals indicate that, in addition to surface area, effects of pore filling, electrostatic interactions, surface complexation, π–π interactions, and redox reactions may lead to increased performance [239-241].

Another novel trend is the production of hybrid biochar-based materials combining adsorption and catalytic / degradation properties. Outside the standard adsorption, the pollutant can be absorbed, and the pollutant can be changed at the same time by adding metal oxides and other functional phases to activated biochar, which is the reason for the simultaneous action [242, 243]. But such multifunctional systems, of course, must be studied very carefully to ensure that the material is stable and can be regenerated and that no metals are released and have secondary environmental effects.

In addition to traditional water pollutant removal applications, activated biochar is also being studied for novel environmental and energy applications such as capturing carbon dioxide. The current study emphasizes the need to be able to control the microporosity, pore-size distribution, and surface chemistry for gas adsorption and other more specialized applications [244, 245]. These developments mimic a shift from broad-based and generic biochar modification to application-specific carbon-material development.

Despite all these developments, a basic question is yet to be addressed: How to make the laboratory-scale activation operations more economically and environmentally viable. The adsorption capacity is in the focus of many recent studies, together with adsorbent recovery, regeneration, consumption of chemicals, energy needs, generation of wastewater, and life-cycle performance [246]. Future research should therefore evaluate the activated biochar based on several combinations of properties, including adsorption efficiency, carbon yield, activation intensity, regeneration, environmental safety, and cost and scalability, rather than maximal adsorption capacity and/or surface area.

7. Research gaps and future directions

Even with the unprecedented advances, there are still several when it comes to the large-scale activation of lignocellulosic biomass to biochar. Current research lacks methodological consistency and extensive worker differences in ratios of impregnations, activation temperature, and holding-time, which complicates inter-study comparison and reproducibility. Standardisation of activation procedures of the different feedstocks and the explanation of the structure of pore, functional group and surface reactivity need to be controlled. The most significant limitation is that traditional activation techniques are high energy, high resource consumption processes. Carbon efficiency and sustainability are often compromised by techniques that use KOH, H_3PO_4 and $ZnCl_2$ as reagents and involve temperatures greater than 700°C, which also make toxic effluents. Future studies should focus on low-temperature pyrolysis, the addition of activation processes and renewable energy support pyrolysis for increased scalability and environmental profits. The mechanistic knowledge of the adsorption process and catalytic process is not complete. Few studies look at the effects of π–π interaction and hydrogen bonding and electrostatic attraction on selectivity and efficiency for a range of pollutants. The combination of systematic investigations with surface chemistry characterization (FTIR, XPS) and molecule simulations is required to design biochar to decontaminate pollutants, especially persistent organic ones such as pharmaceuticals and pesticides. Scalability is another main restraint. Mostly activation studies are performed in small and batch reactors which are not suited for industrial throughput. Related to batch pyrolysis-activation systems, the use of continuous flow systems and the recycling of reagents and heat can improve the efficiency and control of the process. Moreover, life-cycle (LCA) and techno-economic assessments (TEA) should be standardised to check the actual sustainability of these techniques. The other critical one is regeneration/reusability. However, biochar can lose its effectiveness very effortlessly due to poor clogging or oxidation of the surface. Slight thermal or solvent assisted reactivation (SAR) is a low energy method with the potential

of extending material life and reducing costs. Lastly, machine learning (ML) and artificial intelligence (AI) deliver a very strong way of predictive optimization. These instruments can compare feedstock chemistry, activation conditions, and performance metrics; minimize trial and error; and help design application-specific, high-performance biochar. From this point of view, future studies should be directed towards the development of sustainable and data driven activation methods with reduced energy consumption and environmental impact and high performance, scalability, and pollutant specificity, to convert the agricultural residues into progressive functional carbon materials.

8. Conclusion

Lignocellulosic agricultural waste has been converted into activated biochar, which is a potential, viable solution to tackle both the management of agricultural residues and the control of environmental pollution. From physical (CO_2, steam) and chemical (KOH, H_3PO_4, $ZnCl_2$) activation, biochar surface area, porosity, and functional groups can be significantly increased by substantially increasing the physical surface area, porosity, and functional groups of biochar to provide greater adsorption capacities for a range of contaminants, including nutrients, heavy metals, dyes, pesticides, and pharmaceuticals. It is common for activated biochar to outperform conventional adsorbents in the fact that they have cheap costs, renewable origin, and environmental compatibility.

In contrast to agriculture, it is manufactured to save residues that decrease open-field burning and waste buildup, thereby developing soil fertility (SDG 2), clean water (SDG 6), pollution reduction (SDG 3), and the generation of renewable energy in pyrolysis (SDG 7). It also facilitates sequestration of carbon and climate reduction, sustainable use of resources, and restoration of ecosystems SDGs 12 and 15, and is a major aspect of the global environmental and development targets.

The activation process must not be absent in the actual potential of biochar, because agricultural waste such as rice husk, sugarcane bagasse, corn stalks, and coconut shells can convert agricultural waste into highly porous reactive carbon structures. Although chemical activation is more surface responsive, physical and hybrid methods of activation are more effective, energy saving paths that are not very responsive to the principles of sustainability. Green activators, magnetic modification, and heteroatom doping have not only boosted biochar usage in adsorption, catalysis, energy storage, and soil remediation but also green activator emergence. However, as well as these advances, and the shift of the laboratory innovation to industrialization is a challenge. Particularly problematic are high energy demand, inconsistent activation procedures, and lack of standardised performance criteria. Three critical hurdles are high energy demand, different activation protocols, and the lack of standardised performance metrics. Addressing these matters needs an emphasis on scalable, low-energy, and data-driven activation methods; the adoption of life cycle and techno-economic valuations; and the expansion of pollutant-specific design frameworks.

In conclusion, activated biochar is an all-inclusive sustainable product that can be useful in a multi-purpose manner to combine waste valorisation, environmental remediation, and carbon control into one system. Its further development based on the novelty of the activation science, optimisation of the procedures, and assessment of sustainability will be the key to the completion of its potential as one of the pillars of the circular bioeconomy and the international environmental resilience.

Author contributions

Iqra Choudhary: Conceptualization, data analysis, writing—original draft preparation, editing. **Jagriti Dadhwal**: Data analysis and review. **Jyoti Bijarnia**: Data analysis, writing-Editing, and review. **Kirti Lakwal**: Data analysis, writing-editing, and review. **Sandeep Kumar**: Review and supervision. **Bhagawan Dheravath:** Conceptualization, review, and supervision.

All authors have read and agreed to publish the current version of the manuscript.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of Generative AI and AI-assisted technologies in the writing process

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Data Availability

Data will be available upon request.

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