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Transformation of keratinous waste into biochar for sustainable multifunctional applications

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Abstract

Keratin wastes are generated more than 8 million tonnes annually, which largely end up in landfills or incineration. This represents an environmental burden and a significantly underexploited resource with high nitrogen (N) (15–18%) and sulphur (S) (2–5%) that distinguishes itself from the conventional lignocellulosic biomass. The present review consolidates the current understanding of keratin-based biochar across its full value chain. It aims to provide a comprehensive analysis of the chemical composition of the major feedstock, including the processing of wastes using the hydro-pyrolysis and carbon thermolysis methods and examines the kinetics of biochar production. The keratin-based biochar exhibits variability in the yield and quality when subjected to slow and fast-pyrolysis and differs with the technique employed namely thermal pyrolysis, hydrothermal carbonization, catalytic and engineered modification. The multifunctional keratin biochar possesses the capacity to improve soil fertility, pollutant adsorption and removal, and renewable energy retention. The diverse applications are subsequently surveyed, spanning soil-fertility enhancement, pollutant adsorption in water and gas streams, carbon sequestration and renewable-energy storage, while addressing the key challenges in standardization and contamination. Collectively, this review positions keratin waste valorisation as a technically and economically potential route for advancing circular-bioeconomy integration and clean energy transition.

Keywords: Keratinous waste, Biochar, Pyrolysis, Circular economy, Carbonization

1 Introduction

The growing importance of biochar in diverse fields, particularly in agriculture and environmental management, stems from its contribution to carbon sequestration and soil fertility [1]. Globally, different feedstocks are used in the production of biochar, such as crop residues, forestry biomass, and municipal green waste, which are utilized via pyrolytic carbonization [2]. In recent years, keratin-rich wastes such as human and animal hair, feathers, wool and tannery residues have emerged as promising precursors for producing biochar with enhanced physicochemical and functional properties [3]. Human hair and other keratin-rich waste are piled up in huge quantities in landfills, making it essential to channelize this material for various

sustainable uses. Unlike plant-derived biochar, keratin-based biochar provides more N and S with complex structural and protein orientation, broadening its potential applications [4]. Various industries generate keratinous waste at a substantial scale, including salons and temple tonsure waste, poultry industries and leather-processing units. Most of the poultry feather waste comes from some of the top poultry-producing nations, which include China, the USA, Brazil, the European Union (EU), and India. Likewise, for every ton of raw hide and skin converted into leather, approximately 100 kg of hair waste is generated [5], contributing significantly to the collective keratinous waste. India alone produces approximately 3.5 tonnes of human hair waste worth of 188 million USD [6], followed by poultry industries; for example, EU based poultry farming produces 3.2 million tonnes of feather waste [7]. Conventional disposal routes produce gaseous emissions, generate odour, and irretrievably diminish the value of the wastes [8]. In densely populated countries like India, China and Indonesia, this approach could simultaneously address both municipal waste challenges and the growing demand for organic soil enhancers in peri urban agriculture. Adequate segregation and preprocessing can help in enhancing the uniformity of the developed biochar. This can be complemented with the standardization of protocols to ensure uniform product quality, for which one of the primary elements for efficient implementation of biochar production is infrastructure, which would aid in its potential scale-up [9]. In addition, the distance of the pyrolysis facility and the feedstock catchment are also important factors, as closer the distance, the supply chain will be more economically viable thereby, reducing the logistic cost. Poultry feathers come from centralized facilities and thus can be easily collected and processed onsite, which minimizes transportation costs. In contrast, the waste hair from humans is more distributed, thus needing decentralized collection systems. Wool residues are concentrated in textile-processing and tannery wastes are integrated into existing frameworks of the leather industry. Sustainable value chains must thus account for the collection, pre-treatment, and transport of these wastes. Apart from the technological scale up, integration into a broader circular economy model paves the way towards sustainable development [10].

Circular bioeconomy refers to using a renewable biological resource for developing a product, material or energy while generating minimal waste. Keratin is one such underutilized resource that has the potential to boost the circular economy. One of the prominent relevant models is the Industrial Symbiosis model, where waste generated from one industry becomes the feedstock for another (Fig. 1). This implies that hair waste generated in urban salons can be collected and redirected to pyrolysis units as conversion hubs, and agricultural end-users employ biochar to reduce the reliance on synthetic fertilizers [11]. This model builds a symbiotic relationship between the urban sector (salons, slaughterhouses), rural sector (farming and agriculture) and industrial sector (infrastructure for pyrolysis and scale-up). Another prominent model is the Cascade Use Model, where the resources are extracted to have maximum value in subsequent stages, with each stage maintaining or adding value to the material. This applies the principles of reuse, recycling and recovery. This method can be implemented for recycling keratinous waste in cosmetic industries, followed by utilizing residual fraction, which is unsuitable for these uses, can be pyrolysed to biochar. This biochar can be further used as a

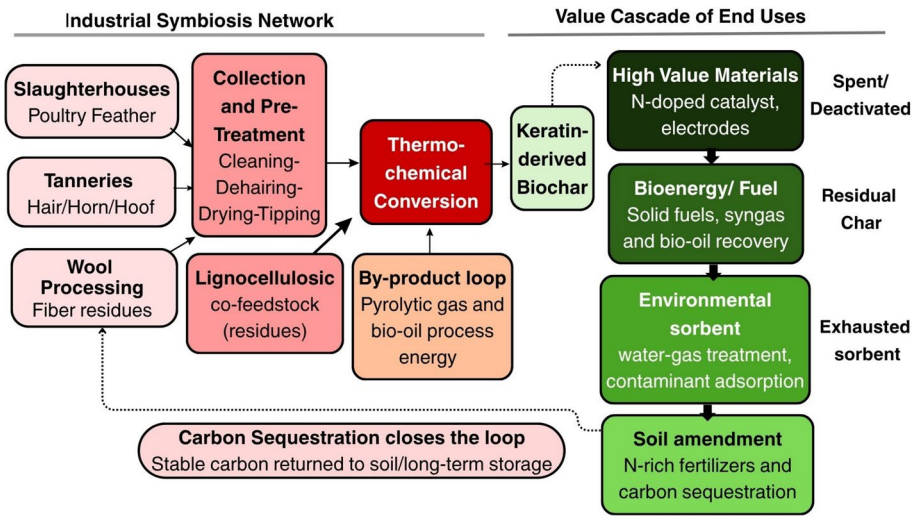

Fig. 1 Circular economy framework for keratin derived biochar (**A**) Industrial symbiosis model (**B**) Value cascade Model

construction composite, thereby maximizing the utility of the resource before it is finally discarded. These by-products enable the system to self-sustain and it can also be used to power the pyrolysis facility. This model is often referred to as the biorefinery model [12].

Building on this concept of resource optimization, it is essential to consider the nature of the feedstock as it influences the properties and downstream applicability of the resulting biochar. Over the years, lignocellulosic feedstocks such as wood, bagasse and crop residues were the conventional route for biochar synthesis. However, keratin-based biochar emerges as a distinct source as they have diverse and abundant surface functional groups present in the keratin backbone, which plays a significant role in the biochar's ability to remediate various environmental pollutants [13]. Human hair and feathers are composed of 90% keratin, a protein-based biopolymer which inherently carries a higher N and S content, unlike cellulose, hemicellulose and lignin, which are largely dominated by a carbon–oxygen framework [14]. This compositional difference emerges as a central advantage, as subjecting keratins to pyrolysis naturally yields self-N-doped biochar, reducing the requirement for an external doping agent such as urea, ammonium salts etc. In addition, keratin's disulphide-crosslinked structure imparts distinct thermal degradation behaviour, often preserving fibrous morphology and porosity differently than lignin- dominated biochar [15]. The existing literature on keratin-based biochar remains fragmented with studies addressing isolated aspects such as types, production and properties in a disconnected manner. To address this gap, the present review provides a comprehensive and integrated assessment of keratin-based biochar along with its holistic overview and recent advances in this field.

2 Keratinous biomass as feedstock

2.1 Chemical composition, emission profile and environmental impact during pyrolysis

Keratin is a fibrous structural protein, high in cysteine and rich in proline. Keratinous feedstocks contain dimeric and oligomeric proteins that combine to form complex structures made of carbon, hydrogen, oxygen, N, and S. These sources of keratin waste

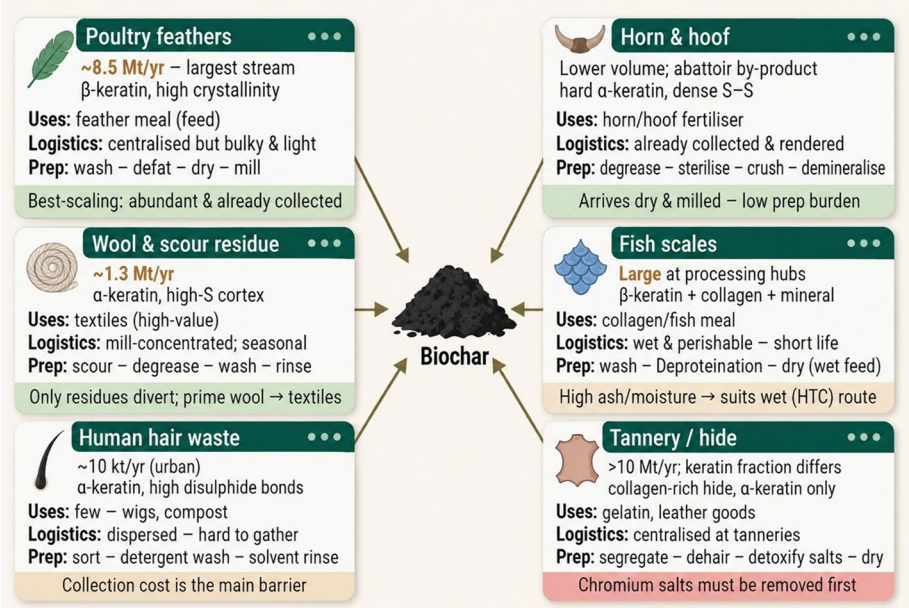

Fig. 2 Diverse sources of keratin waste and comparative overview. The major categories include Poultry feathers, wool, human hair waste, Tannery hides, hoof and horns and fish scales. It shows the availability, logistics and supply chain challenges and preprocessing requirements for biochar preparation

(Fig. 2) differ considerably in their amino acid composition and structural organization. The elemental composition of human and animal hair typically contains 40–50% carbon, 10–18% N, 3–6% S and the remaining hydrogen and oxygen [16]. Table 1 shows the comparative analysis of the elemental composition of keratin waste residues and other prominent lignocellulosic biomasses. Wool and hair are predominantly composed of alpha-keratin and are characterized by relatively high levels of cysteine, which aids in crosslinking, thereby contributing to chemical stability. The cortical cells of hair waste are composed of microfibrils, which have high S proteins. However, these proportions change in accordance with the species, diet, and surface treatments of oils or dyes [17, 18]. Similarly, feathers are one of the most highly concentrated sources of keratin, containing branched structures called barbs and barbules, which provide mechanical strength and resistance to degradation. Feathers carry 85–90% of keratins on dry weight basis with β-keratin constituting the predominant form. The horn and hooves consist of hard α-keratins, which are compactly arranged and making them difficult to process [19].

Structural analysis is important as thermal conversion may trigger rearrangement, along with aromatic reformation, which may result in a change in surface chemistry that potentially alters adsorption, nutrient retention and release properties. Unlike lignocellulosic biomass, where thermal degradation causes breakdown of cellulose, hemicellulose, and lignin, keratin-based feedstocks decompose through pathways governed by their proteinaceous structure and high cysteine content. Chemically bonded N will generate basic surface sites and contribute to the slow-release N. The redox properties of the remaining S will also influence the reactivity of the organic matter toward heavy metals such as Hg and Cd [13]. During pyrolysis, the keratin begins to degrade through disintegration of peptide bonds, with initial volatilization of ammonia and CO_2

Table 1 Comparative analysis of different types of biochar based on feedstock

Feedstock (conditions)	C (%)	N (%)	S (%)	H/C	O/C	Ash	pH	BET ($m^2 g^{-1}$)	Pore/FTIR groups	Cation Exchange Capacity (cmol/kg)	Stability & metals	Reference
Keratin biochar—feather/wool/hair (500–900 °C)	~60–80	~16–18	~1–4	–	–	–	8–10	10–300	Micro-mesoporous, C=O, C–N, amide, pyridinic/pyrrolic N	–	High stability; low intrinsic metals, strong Cr(VI)/dye/TC uptake	[14, 36]
Wood/woody (softwood, 400–600 °C)	~70–90	<1	–	0.2–0.5	0.10–0.20	low (0.1–0.5	5–9	30–140	Micro-macroporous; O–H, C=C, C=O	–	Very high stability; low metals, good PAH sorption	[91]
Rice husk (300–700 °C)	~45–55	0.09–0.11	<0.2	0.053–0.019	0.321–0.170	-	7.5–10	65–330	Micro-mesoporous; Si–O, O–H, C=C	~43–45	High Cd sorption; Si/ash-rich	[92]
Sewage sludge (300–700 °C)	~10–40	~1–7	–	0.74–0.89	0.4–0.8	25%	4–9	4–20	Mesoporous; C=O, O–H, mineral bands	–	Moderate stability; elevated intrinsic metals, immobilises Cr/Cu/Zn	[89]
Crop residue (350–600 °C)	60–70	1.5–2	0.3–0.5	0.64–0.7	0.22–0.4	0.5–21	7–8	–	Symmetrical stretching of -COO^-	3.92–60	Moderate–high stability; strong agronomic value, high nutrient/Cation Exchange capacity	[90, 93]

at lower temperature (< 120 °C). The release of S-containing inorganic species progressively increased, cleaving the disulphide bonds, with the formation of SO_2, H_2S, etc. [20]. As temperature increases further (> 300 °C), the N is redistributed into nitrile like compounds forming heterocyclic structures, while S stabilizes into thiols, thiazoles, and thiophenes. The N is found to be in aliphatic, aromatic nitriles, pyrroles, pyridines and amides. Chicken feather pyrolysis in the 350–600 °C range shows an optimum char and oil yield at 550 °C, thereby producing high N char (13% N) along with pyrolytic oil rich in amino acid derived residues and the resulting biochar comprises pyridinic, pyrrolic and graphitic N forms, which are particularly useful for electrocatalytic application [21]. The retained N and S functionalities in the solid biochar matrix, in the form of pyrrolic and pyridinic N and thiophenic S, can enhance soil fertility by acting as slow release in the environment, thereby improving the cation exchange capacity and microbial habitat suitability [22].

On the other hand, meta-analytical studies demonstrate that biochar application has varied influence on the soil ammonia volatilization depending upon the soil type, pH of biochar and specific application conditions [23]. The keratin-based biochar imposes considerable risk during volatilization in the absence of adequate processing. Similarly, feather-based keratins pose a risk of formation of hydrogen cyanide attributed to the higher N content. In addition, S species are released as H_2S, SO_2, COS and CS_2 during keratin pyrolysis and these toxic by-products may be in gaseous or liquid fractions, which require sufficient filtration to prevent degrading air quality minimising corrosion issues. Also, keratinous feedstocks may have variable amounts of protein-derived ash and trace inorganic impurities (e.g., Ca, Na, and metals) which are often source and pretreatment-dependent. These impurities have the potential to affect the structure and functional properties of the produced biochar. Thus, mitigation becomes essential, especially during pyrolysis, as toxic compounds can be released as vapor and gas phased as NH_3, HCN, H_2S along with particulate matter. The untreated syngas may lead to corrosion and catalyst deactivation, eventually causing secondary air pollution. Some of the prevalent mitigation strategies include cyclones and filters for the removal of particulate matter. Techniques like wet or alkaline scrubbing are used for S species and catalytic decomposition for NH_3 or HCN removal. Thus, in the production of keratin-based biochar, it is coupled with efficient syngas purification and energy recovery as it reduces uncontrolled degradation, avoids simple waste destruction and produces a value-added heteroatom-functionalized carbon material [24]. Thus, it ensures the keratin derived biochar is environmentally friendly and increases the rate of acceptance by the general public. Moreover, keratin waste, when subjected to conventional disposal routes, it resists natural degradation because of the strong disulphide crosslinked structure. While incineration produces CO_2, NOx, and particulate emissions, landfilling generates leachate and slow degradation, which delivers low economic value, justifying the development of keratin-based biochar, which outperforms the lignocellulosic biochar specifically in N-fertilizer value, CO_2/CH_4 gas separation, and heavy metal adsorption [25].

2.2 Techno-economic analysis

Lignocellulosic biochar exhibits a feedstock cost of about 60–70% to artisan scale unit, followed by 33–34% for specialized continuous reactors. The forest residue biochar

systems show feedstock and capital cost together comprising the majority of minimum selling price (MSP) [26]. On the contrary, keratin waste streams represent a different logistic profile, attributed to their widely distributed sources worldwide and require collection from geographically dispersed slaughterhouses rather than a single harvest zone. There is a stark shift in the cost structure from 'growing-harvesting' cost to 'collection-cleansing-biosecurity compliance handling cost processing'. Lignocellulosic residues typically require size reduction prior to pyrolysis, whereas keratin waste involves a series of pre-processing steps such as dehairing, hydrolytic pre-treatment, degreasing to remove blood, fat, impurities, etc. adding to the cost and energy intensive process. The MSP of slow pyrolysis lignocellulosic biochar typically is in the range of 188–260 USD per tonne [27], which can increase up to 1044 USD per oven dry metric tonne for woodchip-derived biochar [26].

Several strategies can improve the economic competitiveness of keratin biochar. Techniques such as co-pyrolysis with lignocellulosic biomass exploit synergistic interactions that improve yield and product quality while uniformly distributing energy demands. In addition, it has the potential to demonstrate synergistic interactions by feedstock composition and blending ratio; especially N-rich keratin with lignocellulosic material yields mineral-fortified, N-doped biochar of enhanced functional value [28]. Secondly, valorisation of co-products reduces production costs as the sale of by-products such as bio-oil and combustible pyrolytic gas paves the way for further revenue and can act as a source for internal energy requirements. In addition to that, integrating with existing waste infrastructure will strengthen the business model along with the carbon removal credits, as several companies want to offset their emissions and biochar can lock the carbon for a prolonged period [29]. Followed by direct sales of biochar as a soil improver and the tipping fee for tanneries, slaughterhouses and other facilities to dispose of their waste turns a disposal cost into a shared benefit. This layered approach fits into the circular economy goals with growing government and market incentives.

3 Synthesis pathways of keratin-derived biochar

Keratin is a tough and slow-disintegrating biomolecule, and the keratin-based biochar is aptly positioned within the waste, which is valorised at every step in a cascade, thereby attributing value to every fraction. Thus, it is subjected to an advanced combination of thermochemical or catalytic techniques, which play an important role in producing solid (biochar), a liquid (bio-oil) and a gaseous (syngas) fraction, facilitating integrated recovery of energy, chemical and carbon material from a single feedstock. Such closed loop processes and zero waste [Sustainable Development Goal (SDG): 12] designs align with the circular bioeconomy goals.

Some of the prominent documented methods for keratinous waste reformation to biochar are Pyrolysis, Hydrothermal carbonization and Catalytic refining (Fig. 3). Among these, thermal pyrolysis can occur over various time frames, namely slow-pyrolysis and fast-pyrolysis. Hydrothermal carbonization remains one of the most effective techniques as it provides greater biochar outputs while conserving N, S, and biochar-associated functional groups. Therefore, in the catalytic and engineered modifications phase, KOH activation, heteroatom-mediated composite construction, microwave activation, and template-assisted methods of pore engineering are some of the strategies

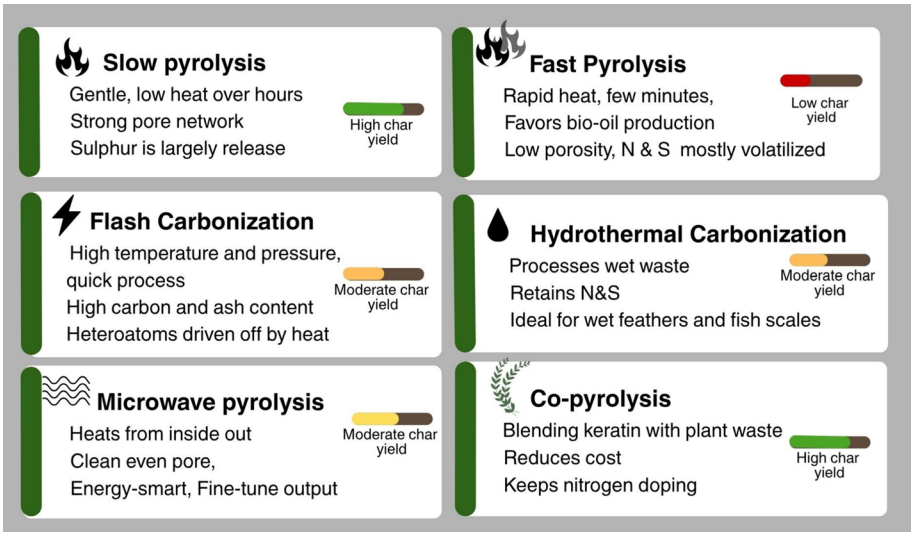

Fig. 3 The synthesis pathways of keratin biochar demonstrating key pyrolysis and carbonization techniques. Different processes and parameters impact yield, pore structure, and carbon content of the biochar

used to improve biochar's surface and structural attributes [30]. The selection of one process over the other has consequences on the biochar properties, such as heteroatom retention, pore geometry and porosity, along with surface and bulk physicochemical properties. The most recent studies demonstrate the various pathways and parameter optimization to achieve keratin-derived biochar with specific functional properties and biochar suitable for applications such as wastewater remediation, energy systems, and soil amendment, underscoring the versatility of biochar.

3.1 Thermal pyrolysis: slow, fast, and microwave-enhanced techniques

Among the various techniques (Fig. 2) for generating biochar from human hair, pyrolysis is regarded as favourable. In the case of slow-pyrolysis, heating biomass in stages to temperatures between <300 °C under non-oxygenated conditions improves the quantity of N and S retained within the char, developing complex aromatic structures. For example, hair subjected to pyrolysis between 210 and 300 °C, when heated slowly, gives maximises the bio-oil yield (97%) with high carbon content (89.32%) biochar [31]. In the case of fast-pyrolysis, however, where the temperature ranges between 500 and 1000 °C, the yield of biochar lower (12%) while the production of bio-oil is significantly higher with 75% yield. The yield and quality of so developed bio-oil is achieved by minimising the residence time of vapours in hot reaction zone and rapidly cooling it when the vapors are formed [32].

Microwave-assisted pyrolysis has gained interest in recent years because it offers volumetric heating, which minimizes thermal gradients and often results in biochar with improved pore distribution. It has been demonstrated that cow hair undergoing microwave-assisted pyrolysis produces chars with improved adsorption capacity toward dyes [13]. In the same manner, it has been reported that chars sourced from hair and produced in optimized pyrolytic conditions are able to efficiently eliminate pharmaceutical contaminants in wastewater. The outcome of pyrolysis is the result of a combination of

factors, including, but not limited to, temperature, heating rate, and level of feedstock pre-treatment [33].

3.2 Hydrothermal carbonization (HTC)

While higher temperatures increase the surface area and aromaticity, they often lead to the lowered retention of N and S, which later in the process can be compensated through post-pyrolysis chemical or physical activation, which enhances porosity and surface area. HTC is a water-based process that can be conducted at a temperature and pressure range of 180 to 260 °C, allowing for the direct conversion of keratinous biomass without the need for pre-treatment and drying [34]. This is particularly advantageous for the waste hair, which is often collected under moist conditions and retains some amount of moisture. Hydrochar produced under HTC tends to have a higher yield and retention of N and S compared to pyrolysis at high temperatures, despite having a lower surface area and more porosity [35]. Cow hair waste was subjected to direct carbonization after pre-treatment and exposed to KOH activation under temperature-programmed heat treatment to produce biochar [36]. The study also shows the possibility of keratin powder extracted from the cow hair waste to produce biochar through carbonization combined with MgO template treatment. Therefore, human and animal hair waste can be processed by similar techniques via carbonization or physical/chemical treatment depending upon the required porosity**.** The porosity is highly influenced by the processes employed for generating the biochar, which forms micropores, mesopores and macropores, which have varied applications.

Retention of functional groups and layering of pores is further refined by catalyst-assisted HTC. It has been reported that metal salts and acid catalysts can stabilize N functionalities and form chars with better adsorption [37]. Similarly, the addition of catalysts in HTC processes optimizes yield and surface chemistry of the product, especially biochar from protein-rich waste biomass. HTC is also advantageous for keratinous waste because of the partial cleavage of disulfide bonds, which increases the abundance and availability of S-containing groups and enables downstream modifications. Ongoing research is investigating the combination of HTC with activation or secondary pyrolysis to yield chars of higher surface area and enhanced surface functionalities [38].

3.3 Catalytic and engineered modifications

Activation of keratin waste via chemical methods with KOH and $ZnCl_2$ enhances biochar production by developing a microporous structure and improves the surface area [33]. As discussed above, the catalytic activation leads to the formation of pyridinic-N and pyrrolic N entities, which finds its application to serve as metal free catalysts, degrade organic pollutants and are used in supercapacitors, etc. This targeted modification generates additional active sites, which enhances the adsorption behaviour. While the research on composites of biochar is largely limited to hair, chars from proteinaceous biomass-derived research suggest enhanced chars with respect to the redox and adsorption properties. Pre- and post-activation pyrolysis hair chars have been observed to improve dye removal efficiencies, which demonstrates the influence of the modification changes on the surface of the material. More sophisticated engineering methods, like microwave activation, template-assisted pore formation, and post-pyrolysis

functionalization with oxidation, amination, or sulfonation, are equally pertinent [37]. A multifaceted set of methods of capture and modification demonstrates the value that can be bestowed on keratinous waste as biochar for a multitude of applications geared toward the environment or industries.

3.4 Biochar yield and comparative analysis

The properties and usefulness of biochar made from hair depend on the controlled parameters during the production of biochar. Temperature is one of the most important variables because it greatly influences final yield, surface area, porosity, and retention of heteroatoms. The retention of N functionalities is generally greater at lower pyrolysis temperatures (300–400 °C), and the yield is higher at lower temperatures. However, porosity and aromaticity are enhanced at higher temperatures (≥ 600 °C), while heteroatom content is diminished. Slow pyrolysis of chicken feather as studied by Li et al. [39] showed 55 wt.% at 300 °C, further reducing to 25 wt% (ground feather powder) at 600 °C, exhibiting a shift from amorphous to more graphitic content as temperature rises. Longer residence times lead to secondary reactions that further increase surface area and graphitic structures, although loss of volatile N and S is greater, resulting in surface area loss (Table 2). Carbon recovery efficiency and the retention of porosity and surface area, as well as the heteroatom N/S quantity and retention, are dependent on activation method, pyrolysis temperature, heating rate, and residence time. On the other hand, for lignocellulosic biomass, increasing the pyrolysis temperature results in a progressive decline in biochar yield, due to the release of volatile products reducing the remaining solid fraction. A systematic mass loss pattern can be observed in thermal degradation of turkey feather, which demonstrates a three-phase behaviour, namely moisture loss, protein/disulphide decomposition and aromatic stabilization [40]. However, the sewage sludge and manure type feedstocks retain more mass as biochar because of high inorganic/ash content. The compiled research listed in Table 2 shows visible trends despite variability from the feedstock and method used.

The rate of heating is also a fundamental determinant for the yield percentage. Heating slowly allows stable solid products to form as keratin degradation occurs. Conversely, heating quickly increases gas and oil fractions and reduces the yield of solid residue [32]. Reactive and uniform chars can also result from feedstock pre-treatment, like washing, drying, and particle size reduction. The adsorption property of biochar is also affected by the techniques of activation applied during or after the pyrolysis process [33]. In HTC, temperature, time, and pH are also extremely important. At lower temperatures, the yield and N retention are greater, but higher temperatures promote aromaticity and decrease heteroatoms. Trade-offs can be partially alleviated using catalysts or modifying agents during HTC [35, 38]. Raising pyrolysis temperature to completely decompose the keratin backbone may compromise the yield. Heating beyond the optimum temperature (200–300 °C) would take a toll on the yield and quality of the material as well.

4 Physicochemical properties of keratin-based biochar

Biochar from different feedstocks has varied morphologies and structural, elemental, and surface compositional differences account for their differential efficacy in pollutant adsorption, nutrient delivery, and catalytic activities [41].

Table 2 The effect of process parameters on yield and physicochemical properties of keratin-derived biochar

Process parameter	Typical range	Effect on yield	Effect on N/S retention	Effect on surface area/porosity	Reference
Pyrolysis temperature	300–700 °C	Yield becomes lower as the temperature becomes higher due to higher volatile release	High retention at 300–400 °C; decline >600 °C	Higher Temperature increases aromaticity, surface area	[31, 32]
Heating rate	Slow (5–10 °C/min) vs fast (> 100 °C/min)	Slow heating produces higher char yield, fast heating favors more bio-oil and gas formation	Slow heating retains more heteroatoms; fast favours volatilization	Fast heating increases micropores but reduces stability	[32]
Residence time	10–120 min	Longer residence time results in progressively lower yield	Extended time reduces N/S retention	Longer residence time promotes graphitization and increases porosity	[31]
Feedstock pretreatment	Washed vs unwashed, particle size reduction	Washing produces a more consistent yield	Washing prevents N/S losses via contaminants	Finer feedstock improves pore uniformity	[13, 33]
Activation (KOH, $ZnCl_2$, H_3PO_4)	600–800 °C + chemical treatment	Chemical activation lowers the final yield due to the burn-off reaction	May remove volatile N/S, enrich stable N forms	Surface area increases significantly and can reach approximately 800–1000 m^2/g	[51]
Hydrothermal conditions	180–260 °C, 1–24 h	Hydrothermal treatment provides a high solid yield	Better N/S retention than pyrolysis	Lower surface area (< 20 m^2/g), but porous after activation	[35]
Catalyst addition	Metal salts, acids	Catalyst addition slightly lowers the yield	Stabilizes N groups, improves retention	Tailors pore distribution & surface chemistry	[38]

4.1 Surface morphology and porosity

Scanning Electron Microscopy (SEM) techniques and scopes, along with Transmission Electron Microscopy (TEM), have shown that keratin biochar has an irregular, heterogeneous form and surface structure [42]. Surface char structures have a rigid, fibrous surface, residues, pores and fissures, and differ from the vascular-formed structures that are typical of wood biochar. The fibrous keratin structure, with its carbonized remains and primitive layer and fragmentation, differs from the dermal vascular frameworks of plant biomass.

Most often, the Brunauer–Emmett–Teller (BET) method is used to determine surface area and porosity. For cow hair-derived biochar processed by KOH activation in the presence of N_2 with initial carbonization at 600 °C followed by activation at 800 °C obtained the highest BET surface area or 1753.075 m^2/g [36]. These increases can be seen through chemical activation with KOH, which aids the construction of micro–mesoporous networks and considerably improves the adsorption efficiency for dyes and pharmaceuticals. In general, hydrochar made through hydrothermal carbonization has lower surface areas compared to pyrolyzed chars. However, their porosity can be significantly increased through activation or secondary pyrolysis [35]. Keratin-derived biochar also has unique pore size distributions. While micropores are predominant in lignocellulosic biochar, keratin-based biochar has higher proportions of mesopores and macropores. This is the result of the disintegration of protein structures and the volatilization during carbonization [43]. These distributions are beneficial for adsorption, especially in the treatment of wastewater, where large organic molecules such as dyes and pharmaceuticals need to be removed.

4.2 Elemental composition and heteroatom retention

Biochar produced from hair contains more N and S than biochar produced from plants. For instance, biochar produced from hair after pyrolysis at 600–700 °C contained 9.61% N and 0.81% S on the surface, demonstrating substantial retention of these functionalities after pyrolysis [41]. This is due to the presence of keratin, which has a high content of cysteine, amino acids like lysine and arginine [44]. Processing conditions influence N and S retention; for instance, labile amines and amides, which are N-containing, are preserved at lower pyrolysis temperatures, while stable pyridinic and graphitic N forms are produced at higher pyrolysis (> 600 °C) temperatures [45]. Poor S retention occurs under hydrothermal conditions, while high pyrolysis temperatures favour S volatilization as H_2S or SO_2 [35]**.** For the biochar derived from hair to retain catalytic activity, the hair biochar must retain sufficient N and S functionalities, as depicted in Table 3. It can be inferred that N functionalities possess the ability to donate charge, catalyse surface activity, and increase surface reactivity, while S functionalities exhibit strong affinities toward soft heavy metals like Hg^{2+} and Cd^{2+} [43]. These characteristics allow hair-derived biochar to possess an additional value that is missing from typical lignocellulosic biochar, and that is the presence of redox-active surfaces and the ability to release nutrients. As such, hair biochar has been proven to expand the environmental and catalytic value of biochar [46].

Table 3 The element composition and the functional properties of biochar derived from keratinous (human hair, feathers, wool, cow hair, bovine horn) and lignocellulosic (wood, straw) feedstocks

Feedstock	Carbon (%)	N (%)	S (%)	Key advantages	Reference
Human hair biochar	55–65	5–12	1–4	High N/S retention, nutrient release, and selective adsorption	[33, 41, 94]
Feather biochar	60–70	8–10	1–2	Protein-based, N-rich, mesoporous	[31, 45]
Wool biochar	55–65	6–9	1–2	High heteroatom content, diverse functional groups	[33]
Wood/straw biochar	65–85	<1	<0.1	High stability, microporosity, structural integrity	[2]
Cow hair biochar	55–65	5–10	1–2	High surface area potential, good electrochemical response for Li–S cathode composites	[53]
Bovine horn biochar	55–70	6–10	2–3	Ultra-high mesoporous structure, very high tetracycline adsorption capacity	[62]

4.3 Functional groups and nutrient release potential

The keratin structure and its processing pathway together determine surface chemistry in hair-derived biochar. The use of FTIR spectroscopy and X-ray photoelectron spectroscopy (XPS) confirms various functional groups such as amines, amides, thiols, sulfones, hydroxyls, and carboxyl. These signatures suggest that some amino acids, particularly cysteine, lysine, and serine, are partially pyrolyzed or decomposed during hydrothermal conversion [15, 47]. Surface functionality distribution is primarily a function of the processing temperature. Heteroatom-rich pig hair waste contains 14.5 wt% N and 3.4 wt% S in the raw feedstock. During pyrolysis, amide, carboxylic acid, aromatic compounds, C-S related functionalities were detected. Deamination was observed between 200 and 480 °C, while C-S bands were detected near 240 °C. Carbonization became dominant above 500 °C promoting the formation of N-, O- and S-doped hair derived biochar [48]. The higher the stability of the carbon matrix, the more functional trade-offs exist. Low-temperature chars facilitate nutrient release while higher-temperature chars are likely to adsorb pollutants or engage in catalytic activity.

As a slow-release source of nutrients, hair-derived biochar holds unique potential value. Chars made at intermediate temperatures have been shown to release ammonium and nitrate gradually, providing a slow and efficient nutrient source compared to synthetic fertilizers, thereby mitigating leaching and increasing plant uptake [49]. Sulphur functionalities and the influence on soil redox potential, especially in flooded, S-deficient soils, and the reduction of soil redox potential, are going to be of critical value [50]. The N biochar and the release of S compounds set keratin-based biochar apart compared to plant-derived biochar, which is generally devoid of heteroatoms. For water treatment, enhanced selective adsorption due to surface functionalities provides unique opportunities for selective adsorption. The N-rich sites interact with acidic organic pollutants and play a role in electron donation. S-rich sites interact with heavy metals. Researchers have great potential in hair-derived biochar for both agronomic purposes and environmental reclamation.

4.4 Comparisons with lignocellulosic biochar

The characteristics of biochar derived from hair differ from traditional lignocellulosic biochar in terms of their composition, morphology, and functional attributes. As shown in Table 3, Char produced from keratinous biomass retains N (5–12 wt%) and S (1–4 wt%) even after high-temperature conversions due to the heteroatoms found in cysteine and lysine-rich keratin backbones. This is markedly different from biochar produced from wood and crop residues, which is predominantly carbonaceous, low in N and S, has vascular pore networks mostly microporous, and lacks chemical diversity. There is a functional divergence due to the differences in composition. The stability and porosity of lignocellulosic biochar have earned them a reputation for being suitable for soil amendments and long-term carbon sequestration, but they have a low nutrient release capacity and require external fertilization. In environmental remediation, plant-based chars can efficiently adsorb hydrophobic organic pollutants due to their microporosity, but have little affinity for ionic or metalated species, which require chemical modification. Hair-derived chars, enriched with functional groups, amino and thiol, have better bonding with heavy metals and polar organics, which increases their adsorption capacity [13].

Nonetheless, lignocellulosic biochar frequently attains greater BET surface areas, mechanical integrity, and pyrolysis efficiency, particularly post-activation [51]. This enables greater potential for carbon sequestration and electrochemical applications. Hence, hair-based biochar should not be perceived as substitutes, but as complementary materials, filling functional gaps in nutrient release, heteroatom enrichment, and selective adsorption. For example, the co-pyrolysis of keratinous residues with plant biomass aims to capture the structural properties of lignocellulose while exploiting the pyrolytic reactivity of keratin [52]. Lastly, keratin-derived biochar is distinguished by N-S heteroatoms, unique fractured morphologies, and mesoporous structure. Given their nutrient-retention properties and selective adsorption capacities, they hold potential for sustainable environmental applications, particularly when process parameters are manipulated to optimize yield in conjunction with porosity and heteroatom retention.

5 Application of keratin-derived biochar

Keratin-derived biochar finds immense application, especially in the field of agriculture, which includes soil enhancement and fertility, heavy metal immobilization from industrial effluents and electrochemical applications largely used for making supercapacitors and other devices for storing energy, as shown in Fig. 4.

5.1 Soil amendment, carbon sequestration, and slow-release nutrient delivery

Biochar made from keratin has added biophysical properties in comparison to other biochar made from bioresidues, attributed to the high cystine, cysteine, and methionine. When keratin undergoes thermochemical conversion, multiple elements are trapped in the carbon structure. These groups give keratin biochar the unique effect of being a nutrient reservoir for slow release [53, 54]. Meanwhile, biochar from

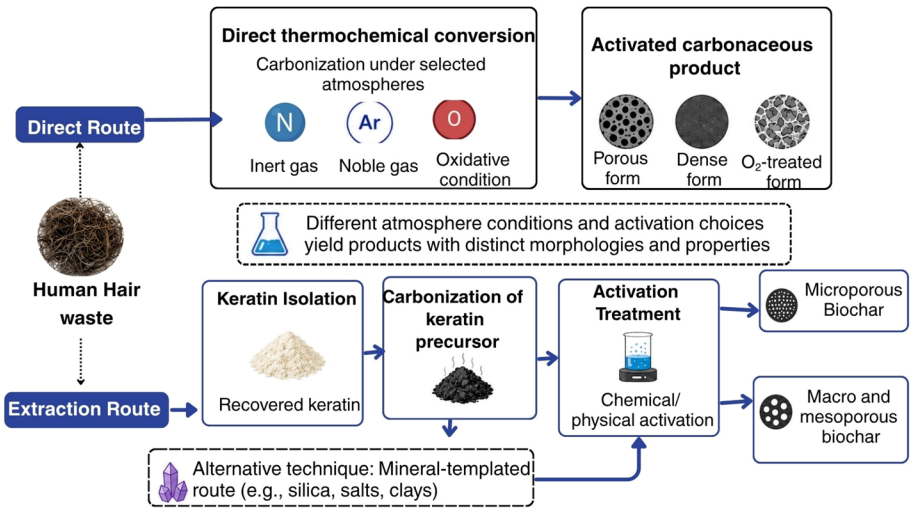

Fig. 4 Schematic flowchart for developing biochar from human/animal hair waste. It shows two different pathways for developing biochar from hair waste by subjecting it to carbonization under different conditions, such as the direct route and extraction route. The direct method involves thermochemical conversion and the activated carbon technique. The second method involves the extraction method via physical and chemical activation, which forms activated keratin-derived carbon and templated porous carbon

lignocellulose is mainly a carbon reservoir comprising comparatively low nutrient content and is supplemented with fertilizers to aid in nutrient accessibility to crops [55, 56].

The unique structure of keratin biochar provides a huge benefit of improving the retention of cation exchange capacity while decreasing its loss. This results in decreased loss of nutrients in keratin biochar. Because of the slow mineralization, keratin biochar improves N efficiency while decreasing losses of N and emissions associated with synthetic fertilizers and greenhouse gases [56]. Keratin biochar contains aromatic carbon that can remain sequestered in soil for decades or centuries, thereby helping restore soil nutrients. Once stabilized in soil, biochar's carbon can be sequestered since it is highly resistant to degradation by microorganisms. The diversion of keratinous waste from landfills or open burning by biochar reduces waste that can contribute to greenhouse gas emissions. This supports the circular bioeconomy. For the sustainable use of agriculture, keratin biochar is preferred over conventional biochar because it offers carbon sequestration along with the recycling of nutrients [57]. The distinctive agronomic value of keratin-derived biochar arises less from the generic soil-conditioning attributes common to all biochar than from biochemical aspects. Nitrogen resides in peptide linkages and amino-acid chains rather than in mineral salts. Improvements in plant and soil health can be attributed to the release of nutrients on soil structure and its effect on promoting beneficial soil microorganisms. The functional groups and heteroatoms help cation exchange and chemical and biological effects and therefore help reduce fertilizer loss and improve fertilizer efficiency. Since it has stable aromatic carbon, it aids long-term carbon sequestration, waste valorization and helps improve the sustainable bioeconomy. Keratin biochar has advantageous properties when compared with typical lignocellulosic biochar and is therefore important for improving soil management and agricultural practices during climate change [58, 59].

5.2 Heavy metal remediation, organic pollutant adsorption, and water treatment

Keratin biochar's unique surface and composition endow it with a particular competitive advantage for commercialisation in the adsorbents market. Traditional biochar based on lignocellulose structures utilises oxygen-based functional groups for adsorption. Such functional groups are less common in keratin biochar. However, keratin biochar is comparatively enriched with pyridinic-N, graphitic-N, amino, thiol, and sulfonic groups, which all have active sites for binding with metal ions and organic pollutants [60]**.** These functional groups enable improved adsorption due to high surface electron density and increased interactions with the adsorbate. Keratin biochar also outperforms other adsorbents due to its unique surface chemistry. S functional groups are high-binding groups. Bonding of metals is possible due to a wide range of interactions that are offered by keratin biochar (ion exchange, surface complexation, electrostatic attraction, pore filling, and precipitation). Such metals include Cd, Cu, Pb, and Hg as well as their ions [61]. Keratin biochar demonstrates potential for the removal of dyes and organic pollutants, antibiotic and pharmaceutical waste streams, as well as other contaminants. This stems from its unique porous structure, as well as the presence of other functional groups that facilitate and enhance multiple forms of surface interactions, enabling efficient adsorption from waste streams [62]. Additionally, it has been shown that chemical activation of keratin biochar from tannery hair wastes also enhances its adsorption capacity, as it preserves the active sites while increasing the surface area of the biochar, which widens its application in water treatment [33]. The presence of heteroatoms minimizes the degree of post-production surface customizations, thereby decreasing production and increasing the biochar's ability to target both inorganic and organic contaminants. Unlike traditional lignocellulosic biochar, keratin biochar improves the ability of both adsorption and catalysis, making it ideal for advanced wastewater treatment.

The naturally occurring heteroatoms and biochar's multiple adsorption pathways make keratin-derived biochar an extremely useful, sustainable adsorbent. This biochar is very useful for the removal of both organic pollutants and heavy metals from wastewater. Further research into both the pyrolysis temperature and activation delay of biochar will likely lead to significant improvements in both biochar's adsorption capabilities and its environmental longevity [63]. The key highlights, as outlined in Table 4, exhibit a wide-ranging functional and versatile potential of keratin-derived biochar in various fields pertaining to the environment and energy. When compared to traditional lignocellulosic biochar, keratin-derived biochar shows several benefits because of the inherent N and S composition. These heteroatom-containing groups provide better cation exchange, retention of nutrients, stronger interactions with both heavy metals and organic pollutants, and negate the need for extensive chemical modifications. Considering the concerns of environmental degradation and climate change, it can promote soil remediation and carbon sequestration, along with improving soil fertility; keratin biochar outperforms other traditional biochar (Fig. 5).

5.3 Energy storage and electrocatalytic applications

Keratin-based biochar finds application in energy storage and electrocatalytic applications. Unlike traditional lignocellulosic biochar, which often requires some sort of

Table 4 Various keratin-based feedstocks utilized for biochar synthesis

Keratin Source	Biochar Application	Mechanism / Key Feature	Case Study and Findings	Reference
Chicken Feather	Applied in potted soil to study the growth of sunflowers	Pyrolyzed at 550 °C	- Ash Content improved - Fixed carbon content improved - Significant improvement in plant height, chlorophyll content and dry weight at 5% application rate	[69]
Chicken feather	Adsorption of heavy metals such as Cd and Pb	KOH modification to increase electronegativity. Studied electrostatic interaction, surface complexity and cation interaction	- KOH modification enhanced the N content in the biochar - Adsorption capacity: 22.324 (Cd) and 119.654 (Pb) $mg^{1-(1/n)}.L^{1/n}.g^{-1}$ - Stable at pH 3–6, efficient in double-ion (Cd + Pb) systems	[38]
Chicken feather	Removal of antibiotics (tetracycline) from wastewater	Biochar developed by two-stage carbonization and modified to form a multilayered graphene phase biochar	- High efficiency of removal was achieved (around 99.65%) for tetracycline - High efficiency was observed even after four regeneration cycles	[70]
Human hair	Adsorption of toxic organic dye such as malachite green and bisphenol-A	Carbonized in a hot air oven at 200 °C for 3 h	- A dosage of 0.5 g/L of human hair-derived biochar achieved a maximum removal efficiency of 96% for malachite green and 83% for bisphenol-A	[71]
Human hair	Development of heteroatom-doped biochar	Pyrolysis carried out under an N atmosphere	- It proved effective as an O, N-doped material, with 21.14% oxygen and 9.61% N present on its surface	[41]
Cow Hair	Composite studied as a cathode for lithium-S batteries	Prepared by the melt-diffusion process	- Activation process increased the surface area and enhanced the S loading capacity - Composite electrodes with 73 wt% S showed an Initial discharge capacity of approximately 1200 mAh/g - Porous structure demonstrated good electrochemical performance	[53]
Cattle hair	Evaluate the treatment of vegetable oil refinery wastewater Secondary use as fertilizer for maize growth	Biochar pyrolyzed at 465 °C and fortified with alum	- Color removal was observed around 98% in 40 min without stirring and 95% in 20 min with stirring - Sulfate removal was 74% in 10 min without stirring and 77% in 20 min with stirring - Recycled adsorbent demonstrated fertilizer potential by improving maize growth	[62]

The exportation potential of every feedstock depends on its variant physicochemical, functional characteristics, and the possible applications. The biochar produced from these keratin sources has been used to enhance soil, remediate contaminants, and store energy

heteroatom chemical doping, keratin biochar has N and S functional groups that pyrolysis renders active catalytic sites [64, 65]. The incorporation of pyridinic-N, pyrrolic-N, graphitic-N, and S functionalities of biochar improves electron transfer kinetics, surface

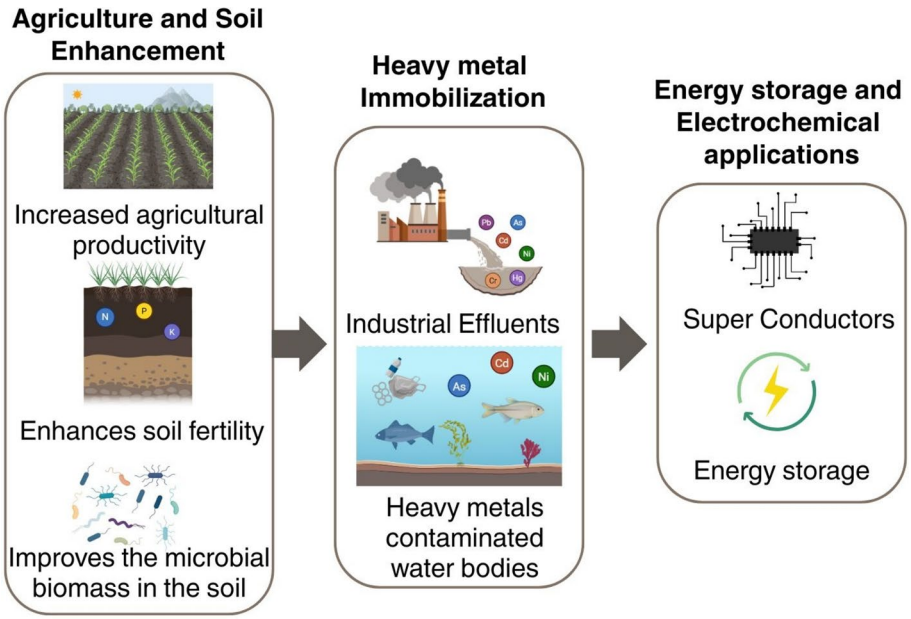

Fig. 5 Various uses of hair-derived biochar across three different fields. Biochar improves soil fertility and enhances microbial activity, mitigates the impacts of heavy metal contaminants in water, and serves as a high surface area of conductive electrode material in electrochemical energy storage systems

wettability, and electrochemical activity, and makes keratin biochar an ideal precursor for carbon-based functional materials.

The high specific surface area and hierarchical porous structure of biochar that has been activated with potassium hydroxide (KOH) or that has undergone template-assisted carbonization is ideal for rapid transport and storage of charge for supercapacitors and batteries. Along with a higher pore volume, these forms of carbonization provide even more active sites for electrochemistry and enhance capacitance and cycling stability [66, 67]. These structural features also assist in decreasing the internal resistance of the system and improving the diffusion of the electrolyte. In the role of an electrocatalyst, N and S co-doped carbon materials from keratin biochar yield improved catalytic activity for the oxygen reduction reactions, oxygen evolution reactions, and hydrogen evolution reactions. Compared to novel metal catalysts, keratin biochar offers an environmentally friendly, low-cost, and sustainable solution for fuel cells and other clean energy applications [68]. Lignocellulosic biochar requires post-synthesis modification for heteroatom doping. Therefore, they have poor electrochemical efficiency, catalytic activity, and stability. Being a heteroatom-doped biochar, keratin biochar offers distinct advantages over conventional biochar, such as reduced preparation time and increased performance. Its unique properties make biochar a viable option to develop sustainable energy storage technology as well as advanced electrocatalysts [67].

5.4 Unique applications of keratin-derived biochar

Beyond the established roles of biochar in soil remediation and agronomic amendment, keratin-based biochar occupies a distinctive position among the carbonaceous materials. Unlike lignocellulosic biochar, which only improves soil structure and is considered a nutrient sink, keratin biochar mineralizes microbial-bound N and S, improving the

biochar's nutrient use readily, helping with the loss of fertilizers and improving soil fertility for long periods of time [69, 70]. The effect of both the conditioning of the soil and the nutrient supply makes it a great amendment for biological farming. Also, another unique property of this biochar is the ability to use it as a precursor for porous carbons that are both N and S-co-doped. Doping with heteroatoms is not needed because they enter the structure of the carbon framework during the pyrolysis, and they naturally occur with the heteroatoms, enabling it to make a self-doped electrode and electrocatalyst platform [71, 72]. Keratin-based biochar is optimal for use in supercapacitors, lithium ion, sodium ion, fuel cells, and catalytic systems for the display enhanced conductivity and superior electrochemical and catalytic performance. For lithium-ion storage, chicken feather has been employed as a Li-ion anode. It exhibited improved electrochemical behaviour with KOH treated samples achieved a discharge capacity of 445.84 mAh g^{-1} and nearlt 100% coulombic efficiency. The improved performance was associated with activation-induced structural modification, reduced crystalline size and enhanced Li-ion transport within the carbon matrix [68].

Due to its developed functional groups, keratin-based biochar serves as an efficient adsorbent in heavy metal and organic pollutant removal, with inherent surface functional groups acting as sites for metal-ion coordination and allowing the binding of a variety of organic pollutants. Thus, compared to conventional biochar, keratin biochar requires minimal surface modifications, which are also cost-effective. Together with its superior ease of use and low cost, keratin-based biochar serves a wide variety of purposes in agriculture, the environment, and energy. Some of these purposes include the slow release of biochar-borne nutrients, the adsorption of selective pollutants, and its high heteroatom electrochemical activity [73].

6 Challenges and bottlenecks in the keratin biochar value chain

The large-scale commercialization of keratin-derived biochar for agricultural, environmental, and energy applications remains cumbersome despite the large advantages of its use. The first obstacle is the diversification of the keratin feedstock. The chemical composition, the S and ash content, the moisture character, and the spatial (or structural) organization of keratin (e.g., tanned leather, fish scales, poultry feathers, hair, etc.) differ from each other. These features affect the biochar yield and the organization of the char pores. These also affect the surface reactivity of the char. All these features also affect how easy it is to standardize production and have a given keratin yield [74].

The collection, transport, and preprocessing of keratinous waste also stall production. While poultry processing is a central operation, other keratin waste residues are drawn from hair salons and the textile industry and therefore derive from many different sources. Even if the quality of the feedstock is maintained, the transport costs and establishment of a collection network all impact the legitimacy of the venture to produce keratin biochar [75]. The cross-linked nature of keratin makes the char difficult to make and, therefore, costly to produce. The thermal decomposition pr protein-rich feedstock generates a complex mixture of gaseous and condensable products like NH_3, H_2S, SO_2 and other volatile organic compounds [76].

Another aspect limiting commercialization is monetary issues. Keratin biochar is of higher cost than standard lignocellulosic biochar. This is due to the cost of the raw

materials, their collection, transportation, the cost associated with their preprocessing, and the energy cost of processing. Integration with the current poultry processing, slaughterhouse, and waste management systems would help in cutting costs; however, large-scale techno-economic studies are lacking [77, 78]. The absence of biochar standards and certification systems worldwide also limits keratin biochar commerce. Confidence in approving regulatory frameworks will be gained by the establishment of biochar standards for feedstock, pyrolysis, testing, and assessment of the biochar quality and environmental safety, and field testing. There is a need for extensive field studies and evaluation of its life cycle and environmental impacts before the keratin-based biochar is made available in the market [79, 80].

7 Future directions

Biochar from keratin has potential for waste-reuse, pollution clean-up, farming, and energy. Its commercial adoption and environmental contributions remain at an emerging stage, with substantial scope for large scale implementation. To address this, future studies should optimise biochar production with desirable properties while minimising the associated environmental impacts. The development of standardized production and application protocols is necessary to facilitate reproducibility and regulatory acceptance [81, 82]. One collaborative pyrolysis strategy is to mix keratin and other biomass from the forest, crops, or algae to improve the costs and biomass yield and produce a biochar with specific properties for environmental and farming needs, while improving the thermal stability and N and S optimum retention [83, 84]. One new area of research, the mixture of artificial intelligence and machine learning with process modelling, can lead to data-driven designs and may help understand and quantify characteristics of biochar, and thus speed the process, cut costs, and improve the reliability of the methods for use on an industrial scale. Keratin-derived biochar may lead to the development of S and N-doped carbon nanomaterials for advanced electrochemical applications. Keratin has both N and S, which can simplify the design of catalysts for oxygen reduction reactions and hydrogen electrocatalysis, fuel cells, supercapacitors, and batteries [85, 86]. One of the major barriers in processing is the rigid di-sulphide bond, which can be treated with novel methods like an enzymatic approach. For example, enzymes like keratinase can be extracted from microorganisms and can potentially aid in loosening the bond. Multiple approaches can be studied to break the complex structure of keratin. Although there is limited study in this arena, it is a potential avenue for scale up at laboratories using advanced techniques like recombinant biotechnology, signal-peptide engineering, and codon optimization in microorganisms, which can potentially improve the keratinase titers for industrial scale applications. In addition to laboratory-scale studies, field trials are needed to assess the long-term stability and safety of keratin-derived biochar in the field. Other long-term testing will be needed to assess the nutrient release and carbon sequestration potential to mitigate greenhouse gas (GHG) emissions in field conditions. A comprehensive life-cycle assessment (LCA) and techno-economic analysis are also needed to assess the energy costs and environmental benefits of using keratin-derived biochar to manage waste relative to more traditional methods of waste management [87]. Another viable approach is the improved use of HTC as it provides several benefits for the management of high moisture keratin-containing waste over pyrolysis, including

much lower operating temperatures, significant energy savings for processing, much better N retention when converted to biochar, and lower emissions of gaseous by-products. Hybrid HTC-pyrolysis systems are even more favourable to manage the environmental impacts when seeking quality biochar [88]. Standardized quality assessment procedures and certification systems for keratin-derived biochar are needed. This includes standardization of the characterization of the biochar feedstock, standardization of the pyrolysis and post-processing parameters and standardization of physicochemical properties, contaminant thresholds along with application recommendations. Integrating keratin-derived biochar into bioeconomy frameworks and circular waste management strategies will be essential for promoting large-scale utilisation [20].

8 Conclusion

Keratin-based biochar is emerging as a potential sustainable material, combining its utility in agriculture with environmental remediation. It converts a waste stream into a value-added product, and it actively contributes to soil fertility enhancement, long-term carbon sequestration, and environmental protection. Keratin biochar thus, effectively links the circular economy and global climate mitigation measures with waste valorization. The amino acid makeup of keratin is what gives it its strength as a feedstock. Keratin biochar has desirable physicochemical characteristics, such as high porosity, changeable surface area, and active functional groups, in addition to its advantages for soil. These characteristics expand its potential applications beyond agriculture into a variety of industries, including wastewater treatment, pollutant adsorption, and even cutting-edge uses like energy storage. Research demonstrates its capacity to eliminate sulphates, heavy metals, and dyes from wastewater, highlighting its adaptability in tackling a variety of environmental issues. However, there are significant obstacles to wider application. The complexity of increasing the production limit, the varied feedstock composition, and the effectiveness of nutrient retention under pyrolysis conditions. The varying feedstock composition, the efficiency of nutrient retention under pyrolysis conditions, and the difficulties of increasing output limit its consistency and reliability. Furthermore, efficient systems for collection, sorting, and preparation are necessary since keratinous wastes come from a range of sources, including urban salons and slaughterhouses. To address these challenges, industrial-scale process development, scientific advancement, and supportive legislation will all be required. Keratin biochar acts as a stable carbon sink, increasing its usefulness from a climatic perspective, with mean residence times in soil ranging from hundreds to millennia. Its usage in farming practices both restores soil and lowers greenhouse gas emissions. Keratin-derived variations may also find commercial success with the increasing acceptance of biochar in carbon markets, assuming reliable monitoring and verification procedures are established.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

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