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A Review of the Unintended Consequences of Biochar in Various Applications

Singaravelu Vivekanandhan[1] | Elif Kaynak[2] | Dong Wang[2] | Vigneshwaran Shanmugam[2] | Aurelio Bifulco[3] | Julio Diarte Almada[4] | Imelda Saran Piri[5] | Zhengyang Wang[6,7] | Lokesh P. Padhye[6,7,8,9] | Nam Kyeun Kim[10] | Michael Försth[2] | Jaime Gonzalez-Libreros[2] | Igor Wachter[11] | Sabrina Karim[12] | Oisik Das[2,13]

[1]Sustainable Materials and Nanotechnology Lab (SMNL), Department of Physics, V.H.N.S.N. College (Autonomous), Virudhunagar, Tamil Nadu, India | [2]Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Luleå, Norrbotten, Sweden | [3]Department of Chemical, Materials and Production Engineering, University of Naples Federico II, Naples, Italy | [4]Umeå School of Architecture, Umeå University, Umeå, Sweden | [5]Faculty of Design and Creative Technologies, School of Future Environments, Auckland University of Technology, Auckland, New Zealand | [6]The New York State Center for Clean Water Technology, Stony Brook University, New York, USA | [7]School of Marine and Atmospheric Sciences, Stony Brook University, New York, USA | [8]Department of Civil Engineering, Stony Brook University, New York, USA | [9]Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand | [10]Department of Mechanical and Mechatronics Engineering, The University of Auckland, Auckland, New Zealand | [11]Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Institute of Integrated Safety, Trnava, Slovakia | [12]Universiti Kuala Lumpur, Institute of Medical Science Technology (UniKL MESTECH), Kajang, Selangor, Malaysia | [13]Universiti Kuala Lumpur, Malaysian Institute of Aviation Technology (UniKL MIAT), Dengkil, Selangor, Malaysia

Correspondence: Singaravelu Vivekanandhan (svivekan@vhnsnc.edu.in) | Oisik Das (oisik.das@ltu.se)

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ABSTRACT

Sustainable development strategies, including biomass waste valorization and life cycle-based carbon management approaches, are being adopted worldwide to mitigate climate change and reduce pollution. Numerous materials or products are under development to meet the demands related to a lowered carbon footprint, higher safety, access to renewable energy, and so on. One such material is biochar, which has been employed in a plethora of applications, areas ranging from soil amendment, polymer composites, energy storage and conversion, building materials, to environmental remediation. However, no two biochars are created equal. This disparity in inherent material properties in biochar means that they should be subjected to effective engineering to tailor their properties to a specific targeted application. This means that a biochar that is suitable for concrete applications may not be appropriate for polymer composite applications. Even biochar properties that were designed for a specific application may not have the desired or expected impact. This can lead to several negative effects of biochar. Hence, this article has collated and reviewed the instances where biochar has had unintended consequences in different applications. Using the knowledge presented herein, researchers can be aware of the potential disadvantages of biochar applications and take necessary steps to abate the negative effects.

1 | Introduction

Due to the global issues related to increasing population, accelerating resource depletion, pollution, advancing climate change, and energy shortages, sustainable solutions are being developed and deployed. One material that can be employed to address a variety of such global challenges is biochar (or biocarbon and engineered char). Biochar is the solid product of the thermochemical processes, mainly pyrolysis and hydrothermal carbonization, wherein biomass (e.g., lignocellulosic or protein-based) is heated above 350°C and 180°C – 350°C, respectively, under limited O_2 or neutral conditions [1–3]. Owing to the unique inherent properties of biochar, which are high surface area, presence of surface functional groups, porous structure, and controllable mechanical properties, it is being explored in a myriad of applications ranging from materials (e.g., polymer composites, concrete), environmental remediation, energy, and in soil [4]. Biochar is gaining popularity because some of its physicochemical properties are akin to conventional carbon-based materials, for example, coal [5]. The production and application of biochar is thought to improve certain disadvantages of fossil carbon-based materials, such as limited reserves, greenhouse gas (GHG) emissions, and a high cost of extraction and purification. Thus, biochar can potentially serve as a low-cost and renewable replacement for fossil carbons and spearhead sustainable development.

Although biochar has been produced and applied (mainly as a soil conditioner) for thousands of years (by ancient Egyptians and in the Amazon basin) [6, 7], its use in material, energy, and environmental applications is fairly new. For example, biochar has been added to various fossil and bio-based polymers to develop composites [1, 8] with functional properties of fire-safety [9], electromagnetic shielding [10], and so on. Biochar is also being increasingly used as a supplementary cementitious material [11]. Biochar is also applied in emerging applications related to energy storage and conversion [12, 13]. Additionally, owing to the possibility of conferring high surface area and cation exchange capacity, biochar has been extensively used for environmental remediation [14], which ranged from heavy metal removal [15], dye removal [16], to wastewater treatment [17]. Furthermore, biochar can be engineered through pyrolysis reactions to exhibit high surface area and pore volume, which have been used to capture CO_2 [18]. Researchers have extensively used biochar as a soil conditioner [19, 20].

Despite the aforementioned applications of biochar, some of which are very novel, using it can have an adverse and/or unintended effect. This is due to both certain inherent properties of biochar as well as suboptimal processing methods that not only lower its efficacy in specific applications but also can have the opposite effect to what was originally expected. In particular, as a result of using contaminated biomass to produce biochar or choosing the incorrect pyrolysis reaction conditions, the final product can contain harmful polyaromatic hydrocarbons, heavy metals, perfluorochemicals, dioxins, free radicals, and volatile organic compounds [21]. Additionally, due to the low bulk density and high surface area of biochar, coupled with the susceptibility toward attrition to form smaller particulates, it can potentially exacerbate air pollution by introducing PM_{10} emissions [22]. Additionally, no two biochars are created equal, that is, biochar has limited reproducibility due to process control and scale-up challenges, as well as due to its intrinsic variability arising from biomass heterogeneity and batch-to-batch differences. Several studies already exist that have reported the negative effect of biochar on soil and plant growth [23–25]. Some studies performing life cycle assessment (LCA) on biochar systems have identified negative environmental impacts related to acidification, eutrophication, and emissions [26]. For the use of biochars in materials (e.g., polymeric composites, concrete) and energy storage and conversion, the biggest issue is designing biochar with certain physico-chemical characteristics, which are needed for these aforementioned specific applications. In other words, inconsistencies in biochar properties occur if the biomass feedstock is varied, if the pyrolysis conditions are altered or if the pre- and post modification of biochar methods are different. However, one of the biggest challenges of biochar is the reproducibility of the required inherent properties needed for specific applications. Furthermore, it is imperative to comprehend, through extensive research, the particular properties of biochars that are conducive to improved performance of various products. For example, in composite applications, biochars made at relatively low pyrolysis temperatures (<400°C–500°C) have good interaction with polar polymers (e.g., polyamide), whereas the ones made at high pyrolysis temperatures (>500°C) are more compatible with nonpolar polymers (e.g., polypropylene) [3]. Thus, if the relationship between biochar's properties and the resulting product's performance is misjudged, adverse effects will be more dominant. The concept of biochar is gaining popularity across the globe to impart sustainable development, and it has also been subjected to green clean-up [27]. It is critical that academia, industry, and policymakers are aware of the potential negative impacts of biochar despite the positive attributes linked to biochar, that is, renewable nature, carbon neutral/negative production method, and so on. This will facilitate a conscious use of biochar in materials, energy, and environmental applications wherein the positive effects are pronounced, and the negative impacts are curbed.

This review article provides a brief overview of the documented and observed negative effects of biochar in various applications related to materials, energy, and environment (soil, water, and air). Although there are quite a few studies that have either reviewed or experimentally studied the adverse effects of biochar in soil and for plant growth, there is a dearth of articles that have reviewed the same for material and energy applications. Hence, the current article will provide information about the negative impacts of biochar in polymer composites, concrete, building materials, energy storage and conversion devices, as well as in environmental remediation and soil applications. The harmful effects of biochar discussed herein are both a result of the authors' own experience while using biochars in certain specific applications, as well as previous studies that have revealed similar outcomes. It is envisaged that this review article would be a one-stop shop for researchers and industry actors to have a realistic outlook toward the potential challenges of biochar and would guide them to effectively avoid and overcome them, leading to biochar's positive role in a sustainable future and a circular economy.

2 | Inherent Negative Properties of Biochar

2.1 | Inconsistencies in Biochar Quality

Significant discrepancies in biochar quality continue to be a critical bottleneck for broader commercial and scientific adoption. The lack of internationally accepted standards for production as well as quality assessment has been a significant hindrance to wider use of biochar, particularly in niche applications where precise control of physicochemical characteristics is essential. While standards such as the International Biochar Initiative (IBI) Standard Version 2.1 [28] and the European Biochar Certificate (EBC) [29] have become significant references, their use is still limited in circumstances requiring stringent performance specifications. For example, the IBI standards provide general requirements such as total carbon, pH, and moisture; however, they do not define specific production processes, feedstock, or functional performance or environmental effect thresholds [28]. Similarly, the EBC provides comprehensive assessments of properties like H/C ratio, ash content, heavy metal concentration, and polycyclic aromatic hydrocarbons (PAHs), yet it lacks mandatory process-specific criteria, making it less effective for ensuring consistency across diverse production pathways [29, 30]. Consequently, this lack of standardization hampers reproducibility and limits the comparability of research outcomes, thereby restricting the advancement of biochar technologies in high-precision sectors. Moreover, the heterogeneity within a single batch of biochar, particularly in large-scale production, raises further concerns over uniformity and quality assurance. These inconsistencies stem from multiple factors, including variability in feedstock composition, pyrolysis parameters, postprocessing treatments, and lack of standardization in characterization techniques. The unpredictable nature of biochar's physicochemical properties undermines its reliability and reproducibility in high-value applications such as materials, energy storage/ conversion, and environmental remediation [3, 31, 32]. Such inconsistencies in biochar quality, arising from variations in feedstock and processing conditions, are reflected in key physicochemical properties, including carbon content, H/C ratio, ash content, surface area, pore structure and electrical conductivity.

2.1.1 | Carbon Content and H/C Ratio

The amount of carbon and the H/C atomic ratio are important signs of how much carbon has formed and how stable the structure of biochar is. A high carbon content with a low H/C ratio shows that the material has desirable aromatic, graphitic structures for uses like electrodes and supercapacitors [33]. However, there are differences due to variations in the types of source biomass material used and the temperature during pyrolysis. For example, Gabhi et al. [34], showed that the carbon content went up from about 87 wt% to about 96 wt% when the pyrolysis temperatures were higher, which greatly improved conductivity. Nevertheless, similar materials processed under different conditions can yield markedly different H/C ratios, posing challenges for reproducibility. In environmental remediation applications, the removal of harmful contaminants by biochar is governed by a combination of factors beyond carbon content alone, including surface area, pore structure, surface functional groups, and the physicochemical properties of the target pollutant. A lower H/C ratio generally indicates greater aromaticity and structural recalcitrance, which is associated with improved stability in soil environments; however, high H/C ratios may suggest a less condensed structure that is more susceptible to decomposition, potentially leading to inconsistent long-term performance. In a recent study [35] on biochars derived from rice straw, wheat straw, corn stover, rape stalk, and cotton stalk (pyrolyzed at 300°C–700°C), the authors found that carbon content increased steadily with temperature, reaching values around 70–80 wt% at 600°C–700°C, while the H/C atomic ratio dropped to below ~0.5 at higher temperatures. The H/C ratio was particularly low for cotton stalk biochar at 700°C, indicating a higher degree of aromaticity. At the same time, oxygen and hydrogen containing functional groups (e.g. -OH, -COOH) declined. Liu et al. [35], also report a strong negative linear correlation ($R^2 > 0.90$) between biochar pH (which rose to ~10.6 at high temperatures) and H/C ratio. These findings confirm that higher temperatures lead not just to more fixed carbon and reduced H/C, but also show that feedstock introduces scatter: the same temperature for different residues still gave modest variation in carbon content and H/C (e.g. rape-stalk vs. wheat-straw) [35].

2.1.2 | Ash Content

Ash represents the inorganic fraction of biochar, rich in minerals and metals (alkaline and alkaline earth). Its content can vary drastically with feedstock (e.g., sewage sludge biochar vs. wood-derived biochar), making standardization difficult. High ash content may increase alkalinity and provide additional sorption sites for heavy metals, aiding remediation. However, excessive ash can obstruct pores, reduce surface area, and lower electrochemical activity in energy storage devices. For example, Bartoli et al. [36], observed that high-ash sewage sludge biochar exhibited poor conductivity ($<10^{-6}$ S/m) compared to low-ash walnut shell biochar. Thus, inconsistency in ash not only impacts contaminant binding but also diminishes reliability in electrode fabrication.

An investigation by Sathyabama & Firdous [37] on agricultural waste biochars (rice husk, sugarcane bagasse, groundnut shells) pyrolyzed at 250°C, 300°C, and 350°C showed that ash content increased up to ~39.12% in certain feedstocks at 350°C, while fixed carbon content reached ~82.4%. It was also found that increasing pyrolysis temperature increased electrical conductivity (from about 0.56 to 4.567 dS/m) and pH (from about 4.0 to 7.7) alongside ash content. These values emphasize how ash does not simply dilute carbon content but interacts with other variables (conductivity, pH) in ways that may help in some remediation tasks (e.g. metal precipitation) but hinder electrical pathways in electrodes. Another example: rice husk biochar (RHB) vs. rice husk ash (RHA) studies [38] report that the ash has much lower organic carbon (~16%) vs. biochar (~46%) but similar iron adsorption capacity (RHB = 5.53 mg Fe^{2+}/g, ashes RHA1 = 6.74, RHA2 = 7.22 mg Fe^{2+}/g). This shows that high ash biochars and ashes may still perform decently in remediation for some ions despite low organic carbon, thus performance is not linearly tied to carbon content but to ash composition and surface chemistry.

2.1.3 | Specific Surface Area (SSA) and Pore Structure

Surface area and porosity strongly affect adsorption and charge storage, yet their variability is one of biochar's most persistent drawbacks. Brunauer, Emmett, Teller (BET) surface areas can differ by an order of magnitude even within the same feedstock depending on pyrolysis conditions or activation treatments. In remediation, micropores aid heavy metal entrapment, while mesopores facilitate diffusion of larger molecules like pharmaceuticals or pesticides. However, Esmaeelnejad et al. [39], showed that finer biochar particles, despite having high porosity, clogged soil pores and decreased hydraulic conductivity. Similarly, Tang et al. [40] revealed that polyethyleneimine (PEI)-modified biochar increased surface area but reduced pore volume drastically, altering Cd immobilization efficiency. This duality makes pore structure optimization highly case-specific, complicating standardized use.

Burachevskaya et al. [41] compared biochars made from wood, sunflower husk, and rice husk and determined the BET SSA values: RHB ranged from 34 to 774 m^2/g, sunflower husk from 7 to 434 m^2/g, and wood from 6 to 557 m^2/g, reflecting strong dependence on both feedstock type and pyrolysis conditions. Wood biochar had the highest BET SSA (612 m^2/g) and dominant macroporosity, while RHB exhibited the highest total pore volume (2.88 cm^3/g) with a predominantly mesoporous character. These structural differences are visually captured in the scanning electron microscopy (SEM) images (Figure 1), which show wood biochar's heterogeneous irregular pore network, sunflower husk's longitudinal slit-like pores, and rice husk's smoother surface with large transverse invaginations. Such morphological distinctions across feedstocks directly influence adsorption performance in remediation and ion transport in electrochemical applications, confirming that pore structure cannot be assumed consistent without tight control of pyrolysis parameters. Another example: in the Aldallah et al. [42]'s work on cedar wood biochar made at 800°C–1100°C, the SSA and pore size increased with temperature; the higher-temperature biochars developed larger pore diameters and more stable pore networks, but with reduced functional group density. These findings show that SSA and pore distribution are not consistent even for the same biomass type unless pyrolysis parameters are tightly controlled, which directly affects both adsorption kinetics in remediation and ion transport in electrochemical applications.

2.1.4 | Electrical Conductivity

Electrical conductivity is fundamental for applications in microbial fuel cells and supercapacitors. Yet it is highly sensitive to pyrolysis temperature, feedstock, and processing. Gabhi et al. [34] found that walnut shell biochars prepared at 500°C exhibited conductivities as low as 10^{-6} S/m. Even at intermediate temperatures around 700°C, feedstock variations introduced orders-of-magnitude differences in conductivity, reflecting the strong dependence on precursor chemistry. Moreover, postprocessing methods such as ball milling and composite blending significantly alter performance; for instance, epoxy composites containing walnut shell biochar reached conductivities of only 0.02 S/m, while those with sewage sludge biochar under identical conditions performed far worse ($<10^{-6}$ S/m). These results emphasize that reproducibility of conductivity remains elusive, even within a controlled thermal processing window. Consistent with these observations, Park et al. [43] demonstrated that paper-derived

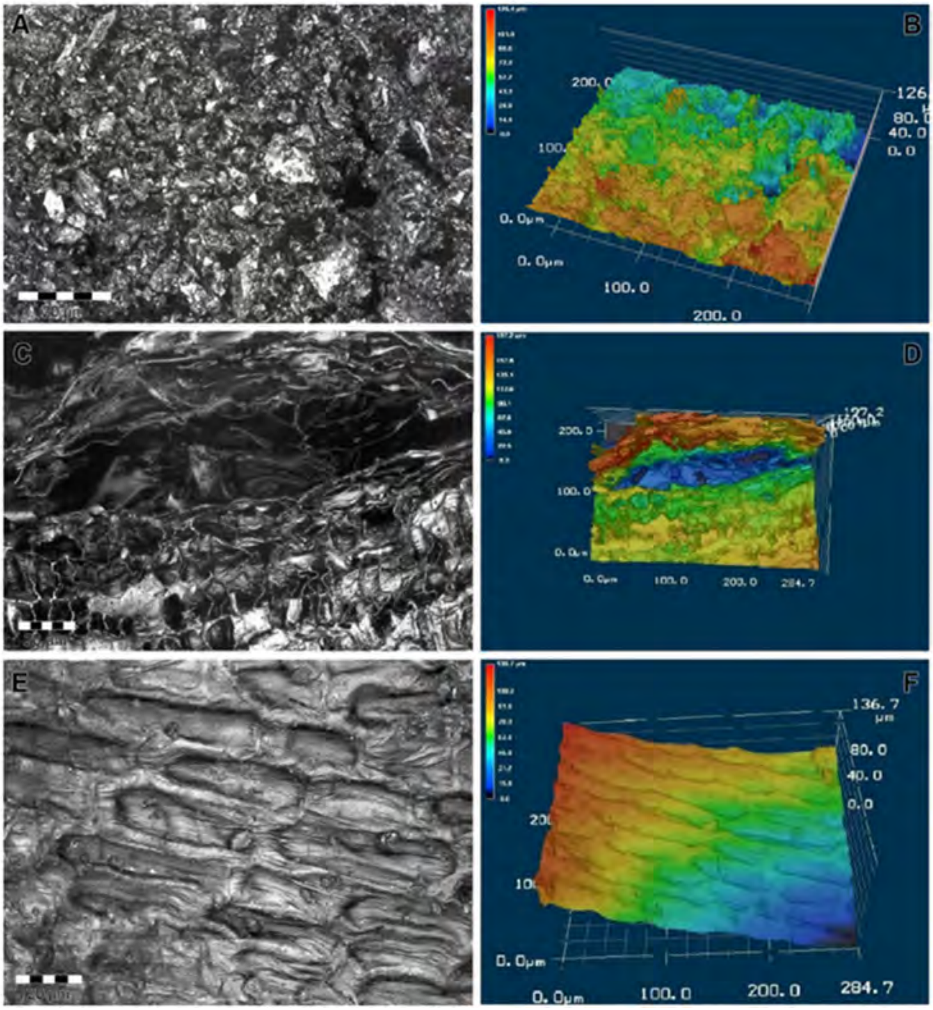

FIGURE 1 | SEM images of biochars derived from (A) wood, (C) sunflower husk, and (E) rice husk, and their corresponding 3D surface models (B,D,F). Adapted from ref. [41]. Open Access 2025, 2026 Springer Nature Limited.

biochars annealed between 600°C–800°C exhibited a sharp rise in terahertz-frequency conductivity from only a few S/m at 600°C to 10–10^2 S/m (tens to hundreds of S/m) at 700°C–800°C. This exponential increase was attributed to enhanced graphitization, loss of oxygenated functional groups, and the development of more ordered carbon domains.

Elsewhere, Kane et al. [44] systematically investigated lignin-derived biochars and reported maximum conductivities spanning 0.002–18.51 S/cm (equivalent to 20–1850 S/m) at pyrolysis temperatures of 900°C–1100°C. Importantly, their meta-analysis also revealed literature values as high as 62.96 S/cm for lignin-based precursors, overlapping with the conductivity range of carbon black (0.5–12 S/cm). Statistical modeling identified oxygen content (O/C ratio) and particle size as the key predictors of conductivity, while lignin isolation routes introduced significant variability even under identical carbonization conditions. This work highlights that feedstock chemistry, beyond temperature alone, must be carefully optimized to achieve electrode-grade performance and reproducibility in biochar-based conductive applications. To complement the discussion on electrical conductivity, it is important to recognize that several additional physicochemical parameters critically influence the performance and reproducibility of biochar across different applications. These parameters extend beyond conductivity alone and include surface chemistry, aging behavior, stability, microbial interactions, mineral catalysis, and structural properties such as porosity and nanostructure. Summarizing these factors in a comparative format provides a broader perspective on the sources of variability reported in the literature. Table 1 provides a comprehensive overview of these factors and the specific parameters through which biochar is commonly characterized. As highlighted in Table 1, the performance of biochar depends on a diverse set of interrelated factors that extend beyond conductivity alone. The heterogeneity across these parameters underscores the need for establishing internationally recognized standards.

Overall, it can be understood that, while biochar holds promise for a wide array of electrical and environmental technologies, its inconsistent quality currently limits its transition from laboratory to real-world deployment. To address these issues, future work must focus on the development of predictive models that correlate production parameters with functional performance, establish application-specific quality benchmarks, and promote the standardization of testing protocols. Only then can the potential of biochar be fully realized without compromising its technical viability or environmental integrity.

2.2 | Self-Heating and Ignition Potential of Biochar

The growing potential for biochar use in a wide range of applications has increased the demand for biochar production over the past decade, owing to its low cost and high CO_2 removal capacity [52, 53]. Production has been growing rapidly to meet the demand for biochar in line with the current efforts to mitigate climate change. According to the European Biochar Industry's report, the biochar production capacity in Europe grew by 41% during 2022–2023 reaching 75,000 tonnes annually [54]. The increasing

TABLE 1 | Comprehensive factors influencing biochar performance and reproducibility in electrical and environmental remediation applications.

Category	Factor	Specific Parameters/Indicators	Reference
Chemical	**Surface chemistry**	O/C and H/C ratios; FTIR functional groups (–COOH, –OH, $–PO_4$); XPS elemental states; zeta potential	[45]
	Stability	Thermal stability (TGA onset/weight loss); chemical resistance (acid/base leaching tests); oxidation resistance (O_2 uptake, aging assays)	[46]
Biological	**Microbial interactions**	Colonization rate (biofilm assays); enzyme activity on surfaces; biodegradation half-life; microbial DNA/RNA sequencing	[47]
	Aging behavior	Change in O/C ratio over time; FTIR band evolution; increase in surface oxygen groups; weathering simulations (UV, humidity)	[47]
Physical	**Mineral catalysis**	ICP-OES/EDX content of Na, K, Ca, Mg, Fe, S; catalytic redox activity (CV curves, oxidation current); ash composition	[46]
	Structural properties	BET surface area (m^2/g); pore size distribution (NLDFT, BJH); particle size (Mastersizer/SEM); Raman ID/IG ratio; degree of graphitization (XRD)	[45]
Electrical/ Optoelectronic	**Conductivity pathways**	Percolation threshold; charge carrier mobility; DC conductivity; impedance spectra (Nyquist, Bode plots)	[48]
Environmental/ External	**pH & Ionic strength effects**	Surface charge variation with pH; buffering capacity; sorption/desorption performance under variable ionic strength	[49]
Mechanical	**Mechanical integrity**	Compressive strength; hardness; friability/attrition resistance during handling and processing	[50]
Hydrophysical	**Wettability and water retention**	Contact angle measurements; hydrophilicity/hydrophobicity index; water holding capacity	[51]
Composite integration	**Interfacial compatibility**	Adhesion with polymers; pull-out/interfacial shear tests; dispersion stability in composites	[1]

trend in the production of biochar brings along additional concerns related to postproduction handling, storage in industrial settings, transportation, and use. The reactive porous nature and high surface area of biochar, the properties that favor many applications, also make it prone to self-heating and ignition [55]. Self-heating and ignition during postproduction and storage may lead to fires resulting in fatalities, injuries to workers, and unnecessary maintenance costs [56]. Despite reported evidence of spontaneous heating of biochar, secondary hazards such as the production of CO, CO_2 and other toxic gases are likely to occur, as previously observed in bituminous coals [57].

The major phenomena leading to the self-heating of biochar are (i) chemical oxidation, (ii) physical activity (i.e., moisture migration, water vapor adsorption), and (iii) biological activity [58]. A few studies have so far examined the self-heating behavior of biochar and the underlying mechanisms. Phounglamcheik et al. [56] studied self-heating behavior of biochar from poplar wood via O_2 chemisorption at low temperatures (50°C–300°C), based on the hypothesis that oxidation governs heat release and temperature increase, provided that the rate of heat generation exceeds the rate of heat dissipation. During the experiments conducted in a closed metal container ($l = 1.20$ m; $w = 1.21$ m; $h = 1.00$ m), the temperature of the biochar increased due to the exothermic oxidation reactions until all the O_2 was consumed. The authors found that producing biochar with higher bulk density (e.g. pellets), using smaller containers, and maintaining lower ambient temperatures reduced the risk of self-heating. However, they also noted that initial temperature of biochar strongly affects the latter two factors, such that when the initial biochar temperature was 230°C, ambient temperatures as low as 12°C were insufficient to prevent thermal runaway; similarly, when the container height exceeded 0.5 m, the higher temperatures recorded inside the containers indicated a greater risk of thermal runaway at an ambient temperature of 25°C. Moreover, woven plastic bags, exhibited a higher risk of thermal runaway than metal containers due to their high O_2 permeability. Palletization of biochar using pyrolysis oil as a binder was proposed to support metallurgical applications where stronger materials are required [59]. However, pellets of biochar produced at 450°C exhibited very high risk of self-heating as the pyrolysis oil covered the pores of biochar, limiting heat dissipation. A secondary heat treatment at high temperatures (>600°C) lowered the self-heating risk by enabling partial volatilization of pyrolysis oil and increasing the porosity of the biochar pellets. Biochar's tendency for self-heating largely depends on its reactivity, which is strongly influenced by the pyrolysis temperature. Restuccia et al. [55], studied the effect of pyrolysis temperatures (350°C–800°C) and feedstock type (i.e., softwood, wheat, and rice-husk) on the minimum ignition temperature of biochar using basket experiments. Softwood biochar produced at 450°C exhibited the highest propensity for self-heating. The reactivity of softwood biochar significantly decreased at higher pyrolysis temperatures (≥550°C), due to the decomposition of lignin and the formation of less reactive carbon. However, biochar produced at lower pyrolysis temperatures (≤600°C) remained more prone to self-heating than the original biomass. Among the studied biochars, rice-husk biochar, which had the highest ash content, was the least prone to self-heating ignition. The authors also employed Frank-Kamenestkii theory to determine the volume of biomass and their respective biochar piles required for self-ignition at ambient temperatures between −10°C and 40°C, using data from basket experiments. Consistent with the results of the basket experiments, RHB, regardless of the pyrolysis temperature, did not exhibit self-heating ignition at ambient temperatures up to 40°C in domestic-scale storage units ($10\,m^3$), whereas softwood biochar pyrolyzed at 450°C exhibited ignition at temperatures as low as 16°C in a storage unit of comparable size. It is worth noting that, in this study, the temperatures employed in basket experiments (90°C–200°C) are not favorable in terms of detecting biological activity as the exothermic biological reactions generally occur at lower temperatures (<75°C) [60].

It is well established that for biomass, biological activity is the predominant initial mechanism leading to self-heating [61]. Microbial activity was also detected in biochar after 4 and 8 weeks of storage at 55°C and 98% relative humidity (RH) [61]. Biochar can support biological activity, such that fungi grow within its pores, degrading refractory carbon [62]. However, the contribution of biological activity to self-heating of biochar is yet to be fully understood. According to the guidelines published by the International Biochar Initiative, adding water can help mitigate the risk of spontaneous ignition of biochar [63]. Although scarcely investigated, the moisture content may significantly influence the self-heating behavior of biochar. A higher moisture content can reduce the tendency of biochar to exothermically adsorb water vapor from the air (as observed in other agricultural biomass materials) and lower its flammability [64–66]. However, the increased moisture may also provide suitable conditions for microbial activity and increase the transportation costs due to the added weight of the material. Further research is required to elucidate the influence of moisture content on the self-heating behavior of biochar under varying storage conditions. Current evidence underscores the importance of optimizing biochar processing parameters, container characteristics, and storage conditions to reduce thermal hazards associated with biochar. A more comprehensive understanding of the prevailing mechanisms that affect self-heating and their relationship to the chemical and physical characteristics of biochar is essential for making informed decisions regarding its postproduction handling, storage, and transportation. The intrinsic physicochemical characteristics of biochar, such as the volatile, mineral, and moisture content, surface area and reactivity, bulk density, and thermal conductivity, not only govern the self-heating behavior but also influence its ignition and fire response under external heat exposure [50]. These properties strongly depend on the pyrolysis temperature and biomass origin (feedstock type) [67]. In general, biochar produced at high temperatures exhibits increased aromaticity, reduced volatile content, and enhanced structural ordering, resulting in improved thermal stability and lower ignition propensity [50]. This temperature-dependent reactivity is also reflected in short- and long-term flammability assessments, where combustion propagation was shown to increase with volatile content, particularly in low-temperature biochars [68]. The study further suggested that fresh biochars may exhibit higher short-term flammability due to reactive surface free radicals and oxygen chemisorption, whereas long-term behavior is primarily governed by retained volatile matter.

When tested in the cone calorimeter (under an external heat flux of $35\,kW/m^2$), biochars produced at 700°C did not ignite and exhibited low peak heat release rate (PHRR) values

(~20–32 kW/m^2) [67]. Similar results (PHRR ≈ 33 kW/m^2) were reported for biochar produced at 900°C under an external heat flux of 50 kW/m^2 where the significant CO production was attributed to the insulating char layer, which limited O_2 penetration. In contrast, lower-temperature biochar exhibited higher heat release. Bamboo biochar produced at 550°C exhibited a relatively higher PHRR (≈48 kW/m^2) under an external heat flux of 35 kW/m^2. Hydrochars (produced at 200°C–260°C) exhibited markedly higher PHRR values; however, increasing hydrothermal carbonization temperature resulted in delayed ignition and corresponding changes in ignition temperature [69]. Distinct flammability characteristics were reported for biochars produced in different reactors and temperatures by Das et al., 2021 [70]. Systematic investigations across reactor types further confirm that pyrolysis temperature strongly governs flammability. Biochars produced at 900°C consistently exhibited lower PHRR values compared to those produced at 300°C [70]. An exception was observed for hydrothermal carbonization (HTC), where biochar produced at 300°C exhibited altered microstructure with retained moisture within the pore network, contributing to reduced PHRR. Intrinsic biochar characteristics, therefore, influence how biochar behaves during combustion and can be tailored through processing conditions to enhance composite fire performance via condensed-phase mechanisms such as char formation and thermal shielding. However, the flammability of biochar-containing composites cannot be inferred solely from the intrinsic characteristics of biochar, as composite fire behavior is additionally governed by matrix decomposition pathways, filler loading and dispersion, and interfacial interactions, which are discussed in detail in Section 3.2.

3 | Negative Effects of Biochar in Various Applications

One of the unique features of biochar is its structural diversity, which is the origin of a wide range of technological applications. Because of their inherent and unique properties, biochars can produce unintended effects in different applications if they are not properly engineered, as outlined below.

3.1 | Negative Effects of Biochar in Polymer Composites

Despite growing interest and studies highlighting biochar's potential to enhance composite performance and contribute to sustainability; several limitations remain in the processing and properties of biochar-added polymer composites. Biochar was incorporated to several thermoplastics and their blends, such as polyamide [71]; polypropylene [72]; high density polyethylene [73]; ultra-high molecular weight polyethylene/linear low density polyethylene [74]; thermoplastic polyurethane; acrylonitrile butadiene styrene; ethylene/vinyl acetate; poly (methyl methacrylate) [75], and bioplastics such as polylactic acid [76] up to a filler ratio of 80 wt.%. The processing of these thermoplastic composites was typically achieved via conventional techniques such as melt blending (e.g., via twin screw extrusion) followed by injection or compression molding; and in a few studies, additive manufacturing methods (i.e. material extrusion 3D printing) were also employed. Nevertheless, challenges remain, as not all processing methods are compatible with the rheological and structural requirements of specific biochar-thermoplastic formulations. For instance, biochar-wheat gluten composites failed to maintain structural integrity when processed via injection molding and could only be produced using compression molding [77]. In contrast, polyamide 11-biochar composites exhibited shattering during compression molding due to the lateral heat-shielding effect of biochar, which impeded melt flow. Additionally, if the processing is done using hot pressing/compression molding, the surface finish of biochar-added composites can be inferior. Similarly, a single stage injection molding may also result in poor dispersion of biochar in the polymer matrix [78]. It is necessary to perform melt-blending to ensure proper dispersion. Alternatively, if a single step of hot-pressing processing is employed, then the pressure should be increased gradually to allow the biochar particles to flow uniformly throughout the softened resin.

Epoxy is the predominant matrix material in studies on biochar–thermoset composites [8]. Although a few more recent studies have examined the incorporation of biochar into other thermosetting resins, such as polyester [79] and vinyl ester [80], with composites typically manufactured via the hand layup process, research on biochar's effects on other thermoset matrices remains limited. The filler loadings of biochars applied to epoxy resin were relatively lower (≤ 20 wt.%) [81–86]. At filler loadings above 1 wt.%, when fabricated via 3D printing, biochar particles agglomerated and were poorly dispersed in the epoxy matrix [87]. These agglomerates acted as stress concentration points under mechanical loading, resulting in premature failure of the composites. The mechanical shortcomings are often closely related to the physicochemical characteristics of biochar.

Since biochar produced at high temperatures (>700°C) is usually devoid of surface functional groups, its interaction with the polymer matrix occurs primarily through mechanical interlocking as seen in Figure 2 [90, 91]. Thus, the porosity and surface area of the biochar are critical factors in determining its compatibility with the polymer matrix, as well as the mechanical and thermal performance of the resulting composites [8, 89, 92, 93]. The porosity and surface functionality are significantly affected by the carbonization temperature, such that, for biochar produced at high temperatures (1100°C), the interfacial adhesion between the ultrahigh molecular weight polyethylene and biochar was weakened due to the formation of a graphite-like crystalline structure with reduced surface area and pore volume and the elimination of oxygen-containing groups (-COOH) [94]. The tendency of biochar to agglomerate restricted the free movement of polymer chains and led to a decrease in the degree of crystallinity of injection molded polypropylene composites [89, 95]. The lower crystallinity, combined with poor interfacial interactions between the biochar and the polypropylene (PP) matrix, resulted in inefficient stress transfer and reduced tensile strength of the composites. This is because most of the biochars added to polymer composites are/were prepared at higher pyrolysis temperatures (ca. > 500°C), which makes it devoid of the majority of the surface functional groups. Thus, even with the use of a compatibiliser, the biochar is not able to chemically adhere to the resin matrix leading to an inferior interfacial bonding and consequently, inefficient stress transfer and lower tensile strength.

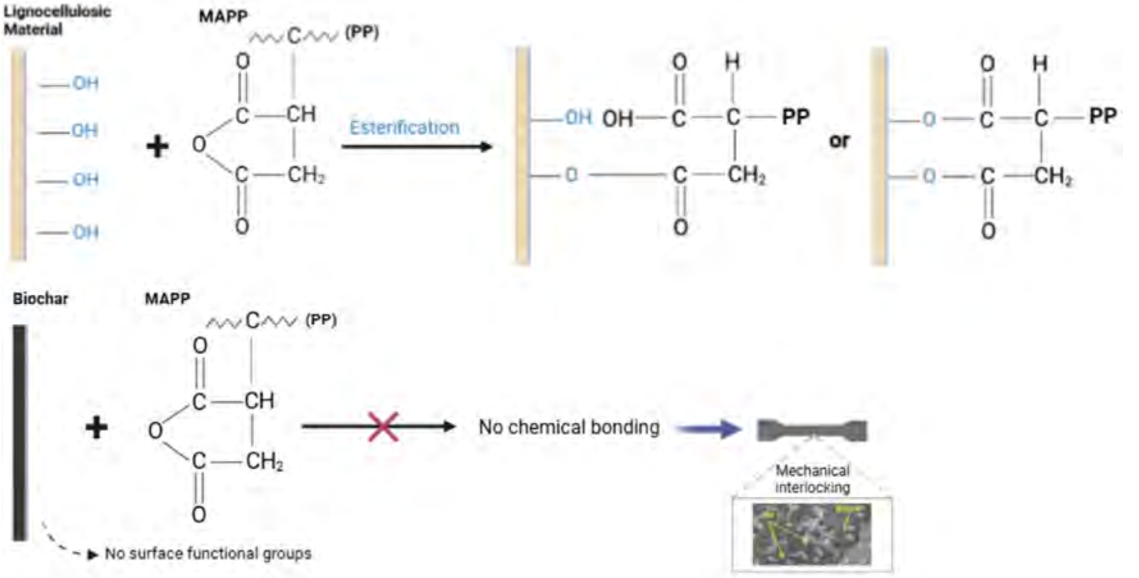

FIGURE 2 | Interaction between maleic anhydride grafted polypropylene and lignocellulosic or biochar surfaces. MAPP: maleic anhydride grafted polypropylene; PP: polypropylene. Scheme-Reproduced from ref. [88]. Open Access 2017, BioResources; SEM image- Adapted with permission from Ref. [89], Copyright 2016, Elsevier.

To alleviate some of these issues, enhancing biochar properties through surface functionalization and further purification (removal of ash) was proposed [95, 96] while the use of compatibilizers such as maleic-anhydride grafted polypropylene (MAPP) was found ineffective in the absence of reactive functional groups on the biochar surface, which is shown in Figure 2 [89, 97]. The mechanical properties of biochar–polymer composites are often compromised due to poor interfacial interactions between the polymer matrix and biochar, which are influenced by the biochar's chemical composition, surface functional groups, porosity, particle size, and surface area [92, 98]. These characteristics are affected by the type and properties of the feedstock in addition to pyrolysis conditions such as temperature, heating rate, and residence time [99]. The negative effects of biochar incorporation on the mechanical properties of polymer composites are summarized in Table 2.

Corncob biochar, which has a lower carbon content than other studied biochar from different biomass (cassava rhizome, durian peel, and pineapple peel), resulted in the lowest Young's modulus (645.49 MPa) in polylactic acid (PLA) composites, indicating weak interactions between the biochar and the polymer matrix [78]. Moreover, the tensile strength of all biochar-PLA composites (50.74–53.22 MPa) was lower than pure PLA (56.63 MPa), and elongation at break values (9.85%–11.35%) were also reduced compared to pure PLA (14.93%). A carbon-rich biochar is typically obtained at higher pyrolysis temperatures, and a higher carbon content is often associated with better reinforcement and infiltration effects in polymeric matrices, which improve mechanical interlocking, and thus, tensile strength of composites [90]. When carbon black was partially substituted (25 wt.%) with biochar derived from agricultural wastes, namely rice straw, date palm fiber, and giant reed, in ethylene propylene diene monomer rubber (EPDM) composites, the tensile strength decreased in all composites except the one containing rice straw biochar [102]. This behavior was attributed to the higher silica content of rice straw biochar (22.4 wt.%) compared to date palm fiber and giant reed biochars (3.68 wt.% and 1.99 wt.%, respectively). A gradual decrease in tensile strength was observed with increasing biochar loading. Complete replacement of carbon black with biochar led to a substantial decrease in tensile strength.

Besides the chemical composition, the physical characteristics of biochar, such as particle size, also significantly influence the mechanical properties of polymer composites [101]. Finer biochar particles exhibited a larger surface area, which resulted in a higher shear between the biochar and polymeric matrix (PLA) during mixing. This high shear led to the degradation of polymer chains and polymer macromolecules at a filler loading of 20 wt.%, as evidenced by a reduction in 2nd heat glass transition temperature. When fine biochar particles were used, the tensile strength gradually decreased with increasing biochar content beyond 5 wt.% (e.g., 16.28 MPa at 20 wt.% loading). In contrast, coarse biochar particles led to lower tensile strength in PLA composites (20.45 MPa) compared to neat PLA (27.84 MPa), even at a low filler loading (5 wt.%). As previously discussed, the reduced surface area of larger biochar particles limits interfacial adhesion between the biochar and the polymer matrix.

The effect of feedstock type on the properties of biochar-polymer composites remains underexplored, despite a few studies presenting in-depth investigations. Hernandez-Charpak et al. [100] studied the effects of biochar derived from two feedstocks (i.e., dairy manure and wood chips), incorporated at 10 wt.% into three polymeric matrices (i.e. PP, polycaprolactone, and PLA). In polycaprolactone (PCA) and PP matrices, composites with wood chip biochar exhibited inferior mechanical properties (tensile strength and elongation at break) than those with dairy manure biochar, due to the lower porosity of wood chip biochar, and thus, weaker interfacial adhesion. Conversely, in PLA, wood chip biochar produced better mechanical properties than dairy manure biochar, albeit reduced compared to the neat polymer. This was mainly attributed to the

TABLE 2 | Biochar–polymer composites: biomass, pyrolysis temperature, processing method, and (negative) effects on thermal and mechanical properties.

Matrix polymer	Biomass	Pyrolysis temperature	Biochar loading	Processing method	Thermal Properties	Mechanical Properties	Ref.
PP	Pine wood	900°C	0–35wt.%	Extrusion/melt blending Compression molding	Crystallisation shifts to higher temperatures. Crystallinity decreases.	Elongation decreases. Similar tensile strength.	[90]
PP	Pine wood	900°C	24–36wt.%	Extrusion/melt blending Injection molding	Crystallisation shifts to higher temperatures.	Tensile strength decreases.	[97]
PP	Date palm	700, 900°C	0–10wt.%	Melt blending Injection molding	Crystallisation shifts to higher temperatures. Crystallinity decreases.	Tensile strength decreases. Elongation decreases.	[95]
PP	Dairy manure, wood chip	550°C	10 wt.%	Melt blending Compression molding	Similar crystallinity. Thermal stability increases.	Tensile strength decreases. Elongation decreases.	[100]
PLA	Cassava rhizome, durian peel, pineapple peel, corncob	400-600°C	0.25wt.%	Injection molding	—	Tensile strength decreases. Elongation decreases. Elastic modulus decreases (only in corncob biochar).	[78]
PLA	Waste coffee ground	800±25°C	0–20 wt.%	Melt mixing Laser cutting	Glass transition temperature decreases. Polymer degradation at 20 wt.% fine biochar.	Tensile strength decreases with coarse biochar particles and at high loadings.	[101]
PLA	Dairy manure, wood chip	550°C	10 wt.%	Melt blending Compression molding	Crystallinity decreases. Thermal stability decreases (for dairy manure biochar only).	Tensile strength decreases. Elongation decreases.	[4]
PCA	Dairy manure, wood chip	550°C	10 wt.%	Melt blending Compression molding	Similar crystallinity. Thermal stability decreases (for dairy manure biochar only).	Tensile strength decreases. Elongation decreases.	[100]
EPDM	Rice straw, date palm fiber, giant reed	400°C	0–40phr	Two roll milling	—	Tensile strength decreases (except for RHB at low loading). Elongation decreases. Hardness decreases (at high biochar loadings only).	[102]
Epoxy	Arhar stalk, Bael shell	800°C	0–6 wt.%	Hand layup curing	—	Above 4 wt.% biochar loading: Tensile strength decreases, Flexural strength decreases, Micro hardness decreases.	[103]
Epoxy	Spent coffee ground	800°C	0–3 wt.%	3D printing curing			[87]

(Continues)

TABLE 2 | (Continued)

Matrix polymer	Biomass	Pyrolysis temperature	Biochar loading	Processing method	Thermal Properties	Mechanical Properties	Ref.
					Storage modulus decreases at 3 wt.% biochar loading and with increasing temperature	Above 1 wt.% biochar loading: Flexural modulus decreases, Flexural strength decreases.	
Epoxy	Kitchen bio-waste	800°C	0–30 wt.%	High shear mixing Glass molding Postcuring	—	Tensile strength decreases, then slightly increases with higher biochar loading.	[104]
PU	Wood chip	650°C	0–20 wt.%	Single step free rise foaming	Thermal conductivity increases.	Compressive strength decreases.	[105]

higher moisture content of dairy manure biochar (6 wt.%) compared to the wood chip biochar (2.5 wt.%), which promoted hydrolytic degradation of PLA during processing.

Biochar incorporation improved the electrical conductivity of epoxy composites at a high filler loading (20 wt.%); however, comparable performance properties (permittivity and electrical conductivity) were achieved with multi-walled carbon nanotubes at a filler loading one-fifth that of biochar [81]. Increased biochar loadings (i.e., 20 wt.%) resulted in the loss of mechanical properties in composites due to uneven dispersion of biochar in the epoxy matrix. The mechanical properties (i.e., tensile strength, flexural strength, and microhardness) of biochar–epoxy composites containing Bael shell and arhar stalk biochars deteriorated at filler loadings above 4 wt.% [103]. Notably, arhar stalk biochar–epoxy composites exhibited 15% lower tensile strength than Bael shell biochar–epoxy composites at the same loading (4 wt.%). This difference was also due to the higher carbon content and large porous surface of Bael shell biochar, although the quantitative data provided were limited to the elemental composition of the different biochars. Though the optimal biochar content is determined by mechanical performance, a lower filler ratio is also undesired from a sustainability perspective since it implies that the amount of fossil-based polymer remains high in the composite. Thus, further research is warranted to increase the content of renewable biochar in thermosetting composites and favor its use in additive manufacturing processes.

In line with the attempts to reduce the environmental impacts of building insulation materials, wood chip biochar was used as a filler in rigid polyurethane (PU) foams [105]. The addition of biochar increased the viscosity of the polyol premix, reduced the closed-cell content, and thus, increased the thermal conductivity, potentially compromising thermal insulation performance. Moreover, the apparent density of the foams decreased with the increasing filler content (up to 20 wt.%), resulting in reduced compressive strength. The hydrophobicity of biochar-PLA composites increased with increasing filler content (1–5 wt.%) [106]. A more pronounced effect was observed when biochar produced at a lower temperature (500°C) was used. The increased hydrophobicity reduced the rate of enzymatic hydrolysis and prolonged biodegradation. While delayed biodegradation may be beneficial for certain applications, it has been highlighted that the incorporation of biochar could contribute to the environmental persistence of bioplastics.

In summary, in order to negate or ameliorate the unintended consequences of biochar in polymer composites, it is critical that biochar is customized against the type of polymer resin, the processing method, and the end application. A biochar that is suitable for thermoset may not be used for thermoplastic resin. Hence, it is critical to comprehend what properties of biochar are important for that specific application of the composite (which is linked to the constituents and the processing techniques). For example, if a high stiffness thermoplastic composite is required, then the biochar should be prepared at high pyrolysis temperature (ca. > 700°C) and a retention time of ca. 1 h to impart a high inherent Young's modulus, which would be manifested in the resulting composite. The temperature of biochar production must be carefully selected based on the polarity of the resin used because biochar obtained at <400°C–500°C preserves oxygen-containing functional groups such as aldehydes, hydroxyls, and ketones, which promote compatibility with polar matrices. Conversely, biochar produced at >500°C undergoes a reduction in surface functional groups, resulting in enhanced affinity toward nonpolar resins. Therefore, application-driven design and processing control are indispensable to ensure reliable and optimized performance of biochar-based composites.

3.2 | Negative Effects of Biochar in Polymer Composites as a Flame Retardant

When selecting a material to act as flame retardant (FR) additive for polymers and polymeric composites, the features of its surface chemistry are crucial. These features can directly influence the dispersion of the additive throughout the system, the interface between the filler and the matrix, and its specific FR action during the burning of the polymer/composite. Biochars are currently being explored as a promising constituent for polymeric composites, and several investigations have employed biochar to impart fire-safety [9, 77]. The surface chemistry of biochars is strongly related to the adopted feedstock along with the highest treatment temperature (HTT) and retention time applied at the production stage [107, 108]. The use of biochars as FR for the manufacturing of polymer-based composites involves positive aspects as well as negative ones, which arise from the versatile surface chemistry, chemical composition, and physico-chemical characteristics of these materials. Biochars produced at high HTTs are predominantly aromatic, show poor acidic character, and exhibit a polar surface chemistry, which is portrayed in Figure 3. These biochars, especially the ones with high porosity, can be easily dispersed throughout the polymer matrix and mainly act as a thermal shield and oxygen barrier in the condensed phase during the burning due to their high thermal stability [107]. However, this shielding effect is often not enough to obtain composites with excellent FR behavior, and thus, synergists (e.g., nitrogen- and phosphorus-based compounds acting as charring promoters, intumescent agents, or sources of flame inhibitors) are needed in the polymer matrix as described in Figure 3 [77]. While the use of biochar is advantageous from an economical point of view, the incorporation of other additives (e.g., ammonium polyphosphate (APP), lanosol, phytic acid, urea) may increase the production costs and negatively affect the mechanical properties of final products [109–111].

Biochars produced at lower HTTs have less aromaticity and greater numbers of different acidic and oxygen-containing surface functional groups. Compared to the ones obtained at high HTTs, these biochars exhibit lower thermal stability and more polar character, with a consequent poor dispersion throughout the polymer matrix (shown in Figure 3) [107]. To enable their uniform dispersion, these biochars can be properly functionalized or incorporated into a modified polymer matrix [110]. Owing to the presence of oxygen-containing functional groups on the surface of these biochars and their lower pH, these materials boost the dehydration of the polymer matrix in the condensed phase and favor the formation of abundant carbonaceous residue during the combustion. This residue also plays a role as heat and oxygen barrier, particularly slowing down the thermo-oxidative decomposition phenomena [112]. Though biochars

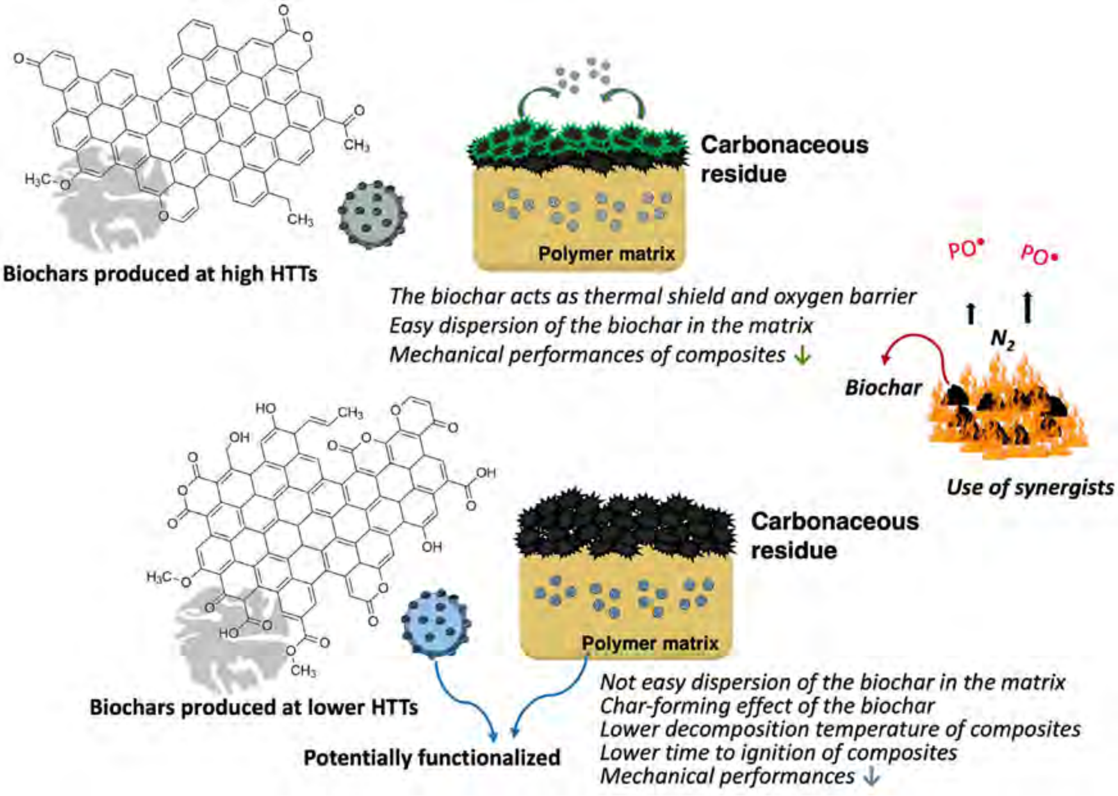

FIGURE 3 | Simplified sketch of drawbacks and advantages related to the use of biochars as flame retardant additive for the preparation of polymer-based composites. Authors' own figure.

obtained at lower temperatures can act as char-formers, they require the use of synergists for the preparation of polymer-based composites with very good fire performances [113]. This again implies an increase in production costs and a decrease in the mechanical performance of the final products [114]. Furthermore, the abundance of functional groups on the surface of biochars produced at lower HTTs frequently causes a significant lowering of the onset decomposition temperature, which can be correlated to shorter time to ignitions (TTIs), as determined by cone calorimetry tests (see Figure 3).

Matta et al. [115] used three different types of biochars, obtained by pyrolysis at 550°C (subsequently annealed at 1000°C for 30 min) of different biomass (i.e., softwood, oil seed rape, and rice husk), as FRs for ethylene-vinyl (EV) acetate-based copolymers. The silica acidic structures, deriving from the presence of phytoliths, in the rice husk gave a biochar lowering the thermo-oxidative stability of final EV-based composites. Irrespective of the type and content of biochar, all the composites were not self-extinguishing due to the high thermal conductivity of the biochar fillers and exhibited lower TTI and ductility (i.e., elongation at break) than the pristine system (shown in Table 3). Mensah et al. used lanosol in combination with biochar, obtained from the pyrolysis at 800°C (1 h) of wood, as FR additives in wheat gluten (WG) bioplastics. While the employment of the fillers together conferred satisfactory values of TTI for the final composites, it resulted in lower tensile properties compared to the pristine system (see Table 3) [116]. As an alternative to lanosol, the same research group proved that the doping of APP into biochar, produced through the pyrolysis at 800°C (1 h) of pine bark, gave better fire performances than lanosol alone in wheat gluten, also slightly increasing the TTI compared to the unfilled WG (see Table 3) [77]. Despite this increase in the TTI, APP-doped biochar led to a detrimental impact on the mechanical properties of FR composites, for example, the maximum tensile stress decreased up to ~30%, with respect to the neat WG. The same APP-doped biochar, when used in polyamide (PA) 11, could not give any well-formed plate by compression molding, as all the samples got shattered without any externally applied force during [77]. Unlike along the vertical direction, the samples did not fuze in the horizontal direction, preventing a cohesive forming of the material. This was attributed to the biochar in the samples, which caused a heat-shielding effect, hindering the flow of the melt more in the lateral direction than the vertical. Thus, the APP-doped biochar was found ineffective in the flame retardation of PA11 bioplastic, due to the adverse influence of the biochar on the vertical heat transfer that impedes the manufacturing of the composites [77].

The flame retardation of polylactic acid (PLA) with biochar alone makes possible the fabrication of fully biodegradable composites. In this context, Kim et al. employed orange peel biochar (OPB), produced by the pyrolysis at 300°C (1 h) of the raw material, as FR for PLA-based composites [118]. To improve the affinity of OPB toward the polymer matrix and enhance its interfacial bonding with the PLA matrix, it was aminated and calcium-crosslinked (CC) through the exploitation of sodium alginate (SA). PLA-based composites containing 4 wt.% of CC-OPB could only achieve V1 rating in the UL-94 vertical burning tests, also giving flame droplets during the burning. Without the addition of SA, composites filled by 4 wt.% of OPB exhibited the lowest tensile strength and elongation at break with respect to all sets of samples (see Table 3). Bifulco et al. used coffee biochar (CB), obtained from the pyrolysis at 800°C (30 min) of spent coffee grounds, as FR additive together with APP and a ternary (Si-Ti-Mg) mixed oxide for the synthesis of epoxy nanocomposites [9]. The modification of epoxy by a silane coupling agent was unavoidable to obtain homogeneous products. However, the acidic character of CB particles and modified resin led to a lower value of TTI compared to the pristine system (see Table 3). The incorporation of APP and Si-Ti-Mg into the silanised epoxy only allowed to obtain V1 class in the UL-94 vertical burning tests, even at a very high (10 wt.%) concentration of CB. Also, CB particles and other synergists acted as topological constraints in the polymer network, causing a less ductile and more brittle material with respect to the unfilled sample (see Table 3). As for the polymer structure, the biochar can be functionalized to improve its dispersion in the matrix and the interface with the organic fraction, so the final composites can keep satisfactory mechanical performances. Ye et al. modified reed charcoal (RC, charring temperature of 450°C) by using graphene oxide, changing the surface character of RC from hydrophilic to hydrophobic, before blending it with polypropylene (PP) to prepare composites with optimized interfacial bond strength [117]. GO-modified RC conferred very good fire behavior to the final PP-based composites but led to a lower TTI than pristine material and a detrimental impact on tensile and flexural strengths, especially for high values of loading (see Table 3).

Elsewhere, Gurusamy et al. [119] investigated the potential of biochar, obtained from the pyrolysis at 600°C of pistachio nut shells and short Turkish hemp fibers for the manufacturing of reinforced polyester resin-based composites with improved fire behavior. At an optimal concentration (15 wt.%) of biochar, it was observed to diminish the flame spread propagation and enhance the mechanical, thermal, and acoustic properties of the composites. A higher (>15 wt.%) content of biochar triggered negative effects on the material’s performance, reducing the mechanical integrity (tensile strength, flexural strength, impact strength) and sound absorption efficiency of final composites. To conclude, the use of biochar as a flame retardant in polymeric materials inherently involves a trade-off, as its drawbacks may compromise the performance of the final composite. In some cases, these adverse effects can outweigh the benefits and lead to suboptimal material properties. However, the development of optimised chemical and processing strategies, such as modifying the polymer matrix or tailoring the surface chemistry of the biochar, offers a promising pathway to mitigate these limitations and enhance overall performance.

3.3 | Negative Effects of Biochar in Concrete

Biochar, as a promising solution for reducing carbon emissions [3], is widely investigated as a potential partial replacement for cement or sand [11]. This approach not only lowers the cost of construction materials but also reduces carbon emissions, as the cement industry is responsible for approximately 8% of the global carbon footprint [120]. Biochar is inert in concrete but can support cement hydration by retaining water, which promotes secondary hydration [121]. A study [122] revealed that converting biomass into biochars to be used as aggregates is beneficial for

TABLE 3 | Major drawbacks related to the use of biochars as flame retardant in polymer-based composites.

Polymeric system	Flame retardant biochar	Flammability	Fire behavior (compared to the control sample)	Mechanical performances (compared to the control sample)	Ref.
Ethylene-vinyl acetate copolymers	Biochars from soft wood, oil seed rape, and rice husk	Best class at UL-94 vertical burning tests: V2	Decrease in time to ignition: up to ∼67%	Decrease in elongation at break (tensile properties): up to ∼80%	[115]
Wheat gluten	Biochar from wood	Not tested	Highest increase in TTI: up to ∼18%	Decrease in maximum tensile strength and modulus of elasticity: up to ∼28% and ∼37%, respectively	[116]
Wheat gluten	Biochar from pine bark	Not tested	Highest increase in TTI: up to ∼19.6%	Decrease in maximum tensile stress: ∼30%	[77]
Epoxy resin	Coffee biochar (CB)	Even adding APP and Si-Ti-Mg into the silanised epoxy only V1 class in the UL-94 vertical burning tests could be achieved, even at a very high (10 wt.%) concentration of CB	Decrease in time to ignition: up to ∼42%	Decrease in elongation at break and fracture strength (flexural properties): ∼77% and ∼64%, respectively	[9]
Polypropylene	Reed charcoal	Not tested	Decrease in time to ignition: up to ∼45%	Decrease in tensile strength and flexural strength: ∼17% and ∼29%, respectively	[117]
Polylactic acid	Orange peel biochar (OPB)	4 wt.% of CC-OPB in the PLA matrix could only give composites showing V1 rating at UL-94 vertical burning tests	Not tested	Tensile strength and elongation at break: • PLA (85.1 MPa, 6.9%) • PLA with 4 wt.% OPB (10.3 MPa, 2.3%) • PLA with 6 wt.% CC-OPB (52.6 MPa, 5.7%)	[118]

concrete's durability, reducing drying shrinkage, and increasing thermal insulation. Biochar acts as a nucleation site, promoting wider and more extensive hydration [123]. Wang et al. proposed that biochar's porous structure enhances CO_2 diffusion, accelerating carbonation and forming stable carbonates [124]. However, biochar lacks pozzolanic activity, and higher replacement levels dilute the cement matrix, reducing hydration products, increasing porosity, and lowering the strength of cementitious composites [125]. Yang and Wang [126] found that increasing biochar content reduces cumulative heat release and $Ca(OH)_2$ formation, with only marginal nucleation benefits. Similarly, another study [127] confirmed that biochar performs best at a 5 wt.% replacement level in cementitious composite, with higher amounts significantly reducing the available cementitious material. While other materials like fly ash and slag can replace 20–60 wt.% of cement without obvious damage of the properties of cementitious composites, researchers [128] found that the minimum biochar content is 0.5–1 wt.% of the binder, with a maximum of 10 wt.%. They also reported that the ideal dosages vary by type: 2–3 wt.% for RHB, 2–5 wt.% for wood biochar, 2–3 wt.% for peanut shell biochar, and 5 wt.% for most others. Replacement above 10 wt.% can impair hydration and weaken structural integrity. Therefore, the inertness of biochar restricts a high dosage to be used in cementitious composites, which significantly hinders the potential application. Biochar has a diverse pore structure resulting from pyrolysis reaction variation and the biomass used [3]. For example, wood-derived biochar pyrolyzed at 550°C (100–400 μm) absorbs 2.20 g/g of water [129]. Smaller biochar particles (45–50 μm) made at 400°C–450°C absorb 2 g/g, while finer biochar particles (10–18 μm) absorb only 0.52 g/g [130]. The varied surface area/porosity of biochar can significantly damage the fresh properties and hardened strength of cementitious composites [11, 131] and potentially create issues for concrete mix design.

3.3.1 | Effect on Workability

As illustrated in Figure 4a, biochar contains both water-accessible and inaccessible pores [140]. While water fully fills accessible pores during soaking, only partial filling occurs in cementitious composite due to limited free water, especially at low water-to-cement (w/c) ratios. As a result, mix designs based on apparent particle density from standards like EN 206:2013+A2:2021 [141] and JGJ/T 12–2019 [142] can unintentionally increase the w/c ratio and total composite volume. The common method in research is weight-based cement replacement with biochar, which harms the workability of cementitious composites. As shown in Figure 4b [133–135], biochar reduces slump from approximately 95% to 73% at 1–5 wt.% replacement, with up to a 40% reduction at 10 wt.%. Figure 4c shows that even 5 wt.% replacement substantially increases the yield stress over time of cementitious composite [136]. A typical solution is increasing the superplasticizer dosage (Figure 4d) [137–139]. A 5 wt.% replacement may require 62% more superplasticizer in cementitious composite. While this improves workability, the high cost of superplasticizer makes it impractical for large-scale use. Therefore, an efficient method should be introduced to alleviate this issue before the practical application.

3.3.2 | Effect on Mechanical Performance

Biochar has an adverse impact at high cement replacement levels in cementitious composites. Figure 5a indicates that incorporating a small amount of biochar (around 2 wt.%) can improve compressive strength by approximately 10%. However, higher dosages result in a continuous decrease in strength with increasing biochar content, with over a 20% reduction observed at a 10 wt.% cement replacement. This could be attributed to the reduced amount of cementitious materials [160, 161], which

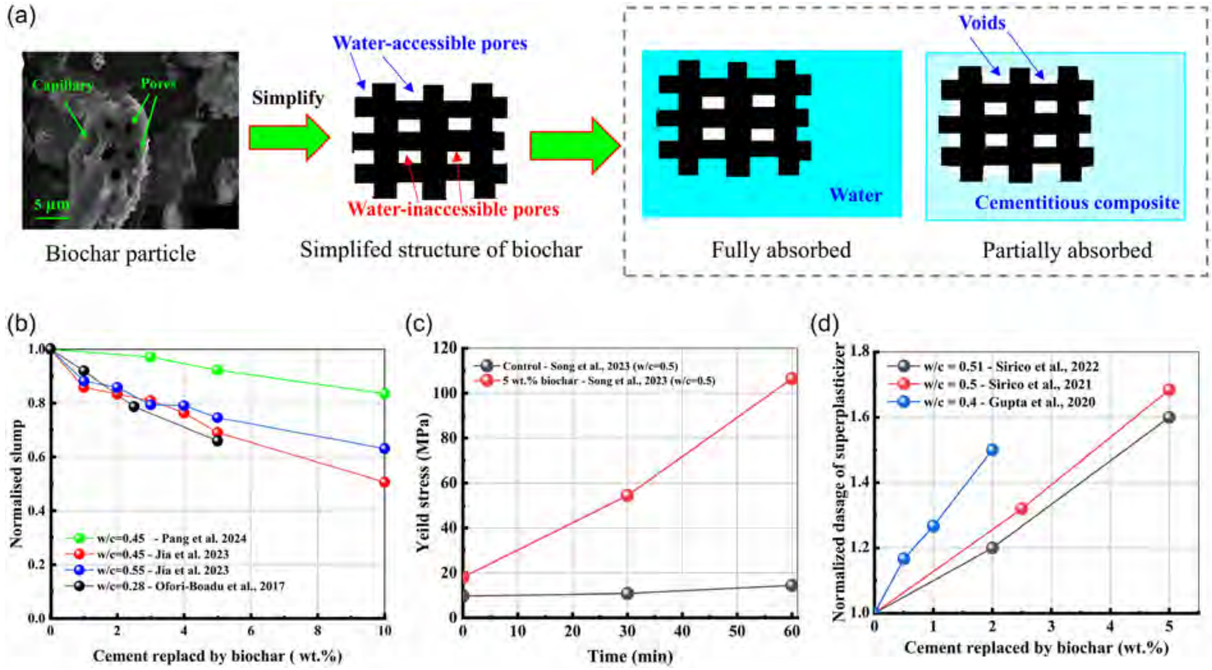

FIGURE 4 | Rheology of cementitious composite with biochar: (a) Water absorbing behavior of biochar in water and cementitious composite, the SEM image is reproduced with permission from ref. [131] Copyright 2025, Elsevier, and the rest of the figure is from an open access publication belonging to ref. [132]; (b) slump reduction with biochar [133–135]; (c) yield stress with biochar over time [136]; and (d) required additional superplasticiser [137–139]. Figures 4b,c, and d are original graphs developed from the data reported in the cited publications.

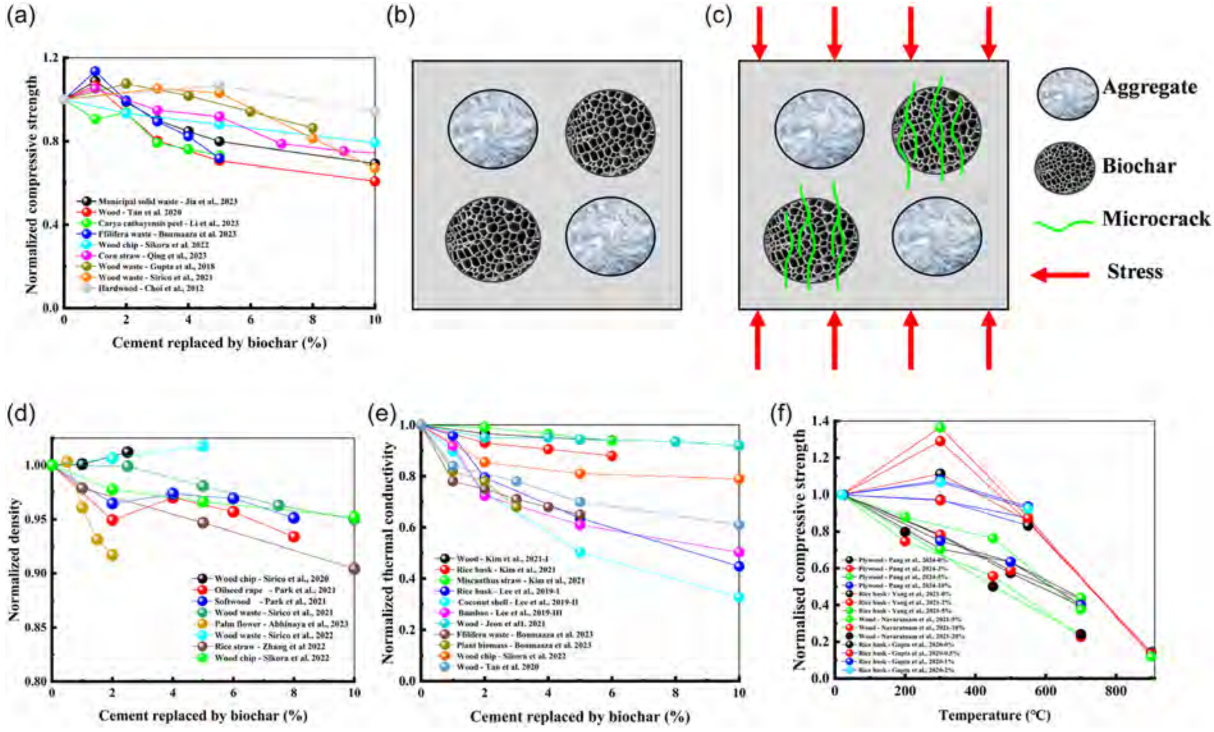

FIGURE 5 | (a) Density of cementitious composite with biochar [137, 138, 143–147]; (b) cementitious composite; (c) microcracks in cementitious composite under compression; (d) effect on compressive strength [134, 138, 144, 148–152]; (e) effect on thermal conductivity [144, 151–156]; and (f) normalized compressive strength [133, 139, 157–159]. Figures 5a,d,e, and f are original graphs developed from the data reported in the cited publications.

cannot be fully compensated by the nucleation and filler effects provided by the biochar [128]. Javed et al. [162] emphasized that the impact of biochar varies depending on its source: biochar derived from bamboo, municipal waste, and certain types of wood (e.g., woodchips, hardwood, softwood) can enhance strength at low replacement levels, while others may have adverse effects. The reduction mechanism shown in Figure 5b indicates that biochar retains its porous structure after cement hydration due to its inertness during the hydration process [3]. When the cementitious composite is under load, as shown in Figure 5c, the porous structure of biochar acts as a weak zone in the matrix, leading to the initiation and propagation of microcracks, which usually lower the mechanical performance of the concrete [163]. This also leads to a decrease in both density and thermal conductivity. As shown in Figure 5d, although biochar can provide a filling effect and serve as nucleation sites [164], slightly improving the density of cementitious composites at low replacement levels (1–2 wt.%), higher replacement levels result in a significant reduction in density, that is, over 10% at 10 wt.% replacement. This reduction in density is the primary reason for the decrease in thermal conductivity. As shown in Figure 5e, the thermal conductivity of cementitious composite continuously decreases with increasing biochar dosage due to the high residual porosity of biochar within the cementitious composite. At a 10 wt.% biochar replacement level, the thermal conductivity decreases by approximately 40%. While this can enhance building insulation [143], it also causes larger temperature gradients during fire exposure, increasing structural damage. Navaratnam et al. [157] found that cementitious composites retained 75%–88% of their strength after heating to 200°C, but with 5 wt.% biochar replacement, strength losses were 12%, 24%, and 62% at 200°C, 450°C, and 700°C, respectively, due to microcracking [157]. Although biochar's porous structure can relieve pore pressure build-up during fire exposure [158], Figure 5f [133, 139, 157, 158] shows that cementitious composites retained only 50% of their strength at 600°C and less than 20% at 800°C after thermal exposure. Therefore, biochar barely has any benefits for imparting fire resistance in cementitious composites. Careful selection and dosage of biochar are critical to balance between thermal insulation and strength in cementitious composites.

3.3.3 | Limitations and Negative Effects of Biochar in Multifunctional Cementitious Composites

In the context of growing environmental concerns and the pressing need to reduce the carbon footprint of construction materials, multifunctional cementitious composites have emerged as a promising solution for enhancing the sustainability of the built environment [165]. Among these, self-healing and self-sensing mortars represent transformative technologies capable of extending the service life of concrete structures while minimizing resource-intensive maintenance and repair operations. Self-healing systems reduce permeability and restore mechanical integrity by autonomously sealing cracks, thus preventing deterioration and reducing the frequency of manual interventions [166]. Self-sensing mortars provide real-time feedback on structural condition through measurable changes in electrical properties, enabling predictive maintenance and safer design [167].

Several studies have demonstrated that biochar, especially when combined with recycled carbon fibers or nano carbon black, contributes to the formation of a stable conductive network that allows real-time monitoring of structural health [168]. These systems benefit from the internal curing effect of biochar, which maintains moisture during early hydration and supports better mechanical and electrical integration, thereby enhancing the reproducibility of the self-sensing response [169]. Despite these advantages, the use of biochar in self-sensing mortars presents several challenges and potential performance drawbacks that must be carefully managed. A major limitation arises from the relatively low intrinsic conductivity of most biochar compared to engineered fillers, such as carbon nanotubes or graphene nanoplatelets, while having a larger variability that is highly dependent on the production temperature, feedstock type, and pyrolysis parameters [34, 170]. While biochar can reduce resistivity in a composite system, it often requires combined use with more conductive additives to achieve a reliable and sensitive electrical response [171]. Experimental results show that hybrid systems, such as those combining biochar with nano carbon black, demonstrate substantially better sensitivity and signal stability, particularly under cyclic loading, whereas biochar alone may not provide sufficient conductivity for early-age or low-strain detection applications [169]. As previously stated in section 2.1, the variability in the physical and chemical properties of biochar can lead to inconsistencies in performance. Differences in feedstock origin, pyrolysis temperature, and particle processing affect surface area, porosity, and ash content, all of which influence the electrical and mechanical behavior of the final composite. Some biochar may contain residual organic compounds or alkaline contents (i.e., the mineral fraction) that interfere with hydration or alter the interfacial properties between the biochar and the cement paste. This can compromise not only the conductivity but also the mechanical integrity of the composite. As explained in our previous research [132], workability and dispersion also pose practical concerns as biochar can significantly reduce the flowability of fresh mortar mixes. This not only complicates mixing and casting but also leads to uneven distribution of the conductive phase within the matrix. Poor dispersion results in non-uniform conductivity and signal instability, making the material unsuitable for accurate sensing applications [172]. While superplasticizers are often used to mitigate workability issues associated with biochar incorporation, poor dispersion and particle agglomeration remain problematic. These can lead to localised conductive paths or voids, ultimately impairing the formation of stable piezoresistive networks and introducing signal noise during sensing operations [173].

Another critical issue is the long-term reliability of the sensing response. Biochar is susceptible to aging effects such as oxidation or carbonation, which can alter its conductivity over time [174]. Environmental exposure, especially in humid or variable temperature conditions, may degrade the conductive network or cause changes in the impedance response of the material [175]. Moreover, the curing process itself can influence the resistivity, as ongoing hydration and pore refinement may increase electrical impedance if the conductive network is not adequately maintained during the setting period [176]. Lastly, achieving an optimal balance between mechanical performance and sensing capability remains a challenge. While small amounts of biochar can enhance both strength and conductivity, higher dosages typically compromise structural integrity. Even when combined with recycled carbon fibers or nanocarbon black, achieving a balance between these properties is challenging since small changes in the mix ratio or dispersion quality can lead to a significant drop in either mechanical performance or sensing efficiency. This sensitivity to composition and processing underscores the need for rigorous mix optimization and quality control in practical applications [169].

For the case of self-healing mortars, biochar has demonstrated to be a promising addition due to its porous structure, chemical stability, and carbon-rich composition [177]. When used as a carrier for bacterial spores involved in microbially induced calcium carbonate precipitation, it enhances the survivability and activity of the microorganisms within the highly alkaline cement matrix [178]. This capacity allows for efficient crack sealing, improved mechanical recovery, and increased impermeability. Biochar particles serve not only as mechanical fillers but also as reservoirs for water and nutrients, fostering microbial metabolism critical to crack healing [179]. Anoop and Palanisamy [178], for instance, showed that coconut shell and wood-derived biochar were shown to preserve bacterial viability for up to 180 days, facilitate the healing of cracks as wide as 0.8 mm, and significantly reduce permeability while promoting calcite crystal formation within the cracks.

Despite the aforementioned benefits, the incorporation of biochar in self-healing mortars is not without challenges and potential drawbacks. One of the primary concerns is the variability in biochar quality. This variability affects pore size distribution, surface chemistry, and nutrient content, all of which influence microbial compatibility and calcite precipitation efficiency. For instance, not all types of biochar exhibit the same compatibility with bacterial strains, such as *Bacillus pumilus*, and some variants may result in poor microbial colonization or even inhibit bacterial growth due to residual toxins or unsuitable pH levels [178]. Another issue is the physical dilution of the cementitious matrix when biochar replaces portions of cement. This substitution can lead to weakened mechanical properties if biochar content is too high, particularly due to the increased porosity and the development of weak interfacial transition zones around biochar particles. Some studies report that while low dosages of biochar improve strength and healing, higher dosages result in reduced compressive strength, decreased flexural performance, and compromised integrity of the healed zones, especially under aggressive environmental conditions [177]. Moreover, biochar's capacity to absorb and retain water can become a double-edged sword. While this property benefits bacterial activation and hydration, excessive water retention may also disturb the moisture balance of the matrix during curing, leading to inconsistent or delayed setting. The swelling behavior of biochar under wet conditions can also interfere with crack width stability, potentially distorting the geometry of healed regions [180].

In terms of long-term performance, biochar particles may serve as preferential zones for microbial colonization, but they can also introduce microstructural heterogeneities that become sites for future cracking or degradation if the biochar itself deteriorates or reacts unfavorably with cement hydration products [130]. In poorly controlled systems, bacterial encapsulation within biochar can suffer from insufficient loading or uneven distribution, resulting in patchy healing or incomplete crack closure. In light of the aforementioned, biochar represents a multifunctional and sustainable additive with the potential to significantly enhance both self-healing and self-sensing capabilities in cementitious materials, contributing to the development of low-carbon, intelligent infrastructure. However, its practical implementation must be carefully balanced to avoid unintended drawbacks. Challenges such as variability in biochar properties, inconsistent conductivity, and adverse effects on mechanical strength and hydration behavior necessitate rigorous optimization of biochar production, dosage, and integration strategies. Future research should prioritize the development of standardized production and characterization protocols, explore hybrid systems incorporating engineered conductive additives, and refine processing methods to ensure uniform dispersion and long-term functional stability. Comprehensive, long-term durability testing under diverse environmental conditions will also be essential to fully realize and scale biochar's multifunctional potential in sustainable construction.

3.4 | Negative Effects of Biochar in Building Materials

The use of biochar in building materials is recent and increasing due to its capacity to act as a carbon sink, among other advantages. Proof of this is the recently inaugurated biochar-concrete prototype service housing exhibited at the 2025 Architecture Biennale in Venice designed by Alejandro Aravena and the ELEMENTAL team in collaboration with HOLCIM [181]. Although this event marks a milestone in its promotion as sustainable alternative, there is still much to know about this complex material. The most common biochar applications in building materials are as cement or aggregate replacement in concrete and in technical applications as thermal insulation. Consequences of biochar in concrete have been particularly addressed in Section 3.3.; thus, this section reviews the potential issues as thermal insulation or storage enhancer, as well as a brief overview of other cross-cutting constrains, and reflection on biomass availability and supply-chain issues.

3.4.1 | Biochar as Thermal Insulation or Storage Enhancer in Composites

Biochar's low thermal conductivity and high porosity have promoted its application in thermal insulation components; however, these properties can lead to issues related to moisture absorption, mechanical stability, and durability. Biochar's high porosity increases water absorption and sorptivity coefficient, directly impacting moisture resistance of insulation building components. In a study of thermal conductivity of biochar-clay composites, Janetti et al. [182] reported that low density biochar-clay mixes increase water absorption of thermal insulation components, thus limiting its application to internal applications only. Similarly, Zhang et al. [183] observed that adding > 40 wt% biochar into gypsum composites can substantially increase water uptake and negatively impact mechanical strength due to moisture-induced problems.

Another important concern is the thermal gradients produced by different thermal conductivities of biochar and gypsum. These gradients produce irregular heat flux around the biochar particles lowering the overall heating of the composite [183]. Although this can increase composite's insulation capacity, differential thermal expansion can lead to warping, delamination, or cracking in the long-term. Uneven thermal flow can produce condensation in specific points degrading the composite over time due to mold or frost damage. Interlayer delamination caused by thermal gradients leads to fracture, delamination, and debonding, and it's a recurrent issue within composites regardless of its fabrication method (e.g., vacuum formed lamination, additive manufacturing, molding, and casting) and surrounding temperature [184]. High porosity of biochar can also lead to more brittle materials. For instance, Nigay et al. [185] observed that the addition of 15 wt% biochar with a particle size of 20 μm in clay composites decreased its initiation fracture toughness by ca. 24% compared to a clay ceramic without biochar. Similarly, Vidakis et al. [73] corroborated that high concentrations of biochar (>10 wt%) in acrylonitrile butadiene styrene (ABS) filaments for 3D printing composite applications can negatively impact rheological properties and produce uneven side surface and ductile fracture surface form with micropores. Finally, from the manufacturing perspective, density variability challenges the fabrication process to achieve uniform biochar distribution within gypsum composite, requiring a careful control of biochar particle size and distribution during manufacturing [183].

3.4.2 | Cross-Cutting Constraints for Biochar Application in Building Materials

Trade-off between environmental benefits and economic costs renders an uncertain future for the large-scale implementation of biochar in building materials. In this sense, Owsianiak et al. [186] reported that economic benefits for biochar production in developing and middle income countries (the study included Ethiopia, Indonesia, Kenya, Peru, Vietnam, and China) were achieved only when low technology and low labor cost are combined. Although this can be positive from a short-term economic aspect, it can incur elevated environmental and social cost. Conversely, investments in more efficient production system (e.g., gasification-based methods) are economically unsustainable, according to the same study. These results are backed by You et al. [187] who found similar barriers to make biochar production more economically feasible in rural China. Elevated implementation cost of gasification-based systems that are more efficient, together with the costs related to collection, transport, and pretreatment, are the major challenges to achieving cost efficiency.

Pandey et al. [188] performed a preliminary techno-economic analysis to assess the cost efficiency of manufacturing thin biochar-enhanced bricks and stone-like veneers for the US market. In their results, the critical importance of *'maintaining reasonable product prices and production rates to ensure economic feasibility'* was underscored. Similarly, elevated and variable production costs were viewed as a major challenge for biochar application as modifier in asphaltic binder [189]. The elevated cost of biochar compared to traditional insulation materials, such as glass fiber and foam, could deter its implementation or limit its use to small amounts. For example, Osman et al. [190] reported case studies that used small biochar amounts, namely 0.5% where the cost impact was minimal. Moreover, biochar-based building materials might also face visual perception challenges akin to similar bio-based products. A study on aesthetic and functional perception of bio-based composites (e.g., wood fiber, regenerated cellulose, coir, sisal, cotton, and flax) determined that visual features, such as high fibrous, porous, rough, and or disordered surface appearance, i.e., inherent qualities of some biobased materials including biochar, may impact consumers' perception [191]. In summary, five critical points are identified that need to be considered when using biochar as a constituent in building materials. Firstly, moisture sensitivity caused by high porosity can lead to durability issues and limiting it to interior applications only, particularly in gypsum and clay composites. Secondly, thermal gradients between biochar and surrounding matrices can degrade materials in the long-term, especially in insulation composites. Thirdly, high biochar content can reduce fracture toughness and increase brittleness in clay-based 3D printed composites. Variable production costs and scalability challenges create an uncertain economic viability in different economic contexts. Lastly, as with other bio-based materials, rough and porous aesthetic qualities may hinder consumer perception and acceptance.

3.4.3 | Feedstock Availability and Supply Chains

Scaling biochar into construction or energy applications introduces feedstock competition with established uses, including soil amendment or energy recovery, as well as regional availability and logistical constrains. Deployment in buildings could be constrained by feedstock supply, logistics cost, and technology level, especially considering that high-efficiency and low-emission systems are capital-intensive while low-tech systems risk variable quality and higher emissions. In this content, regional supply-chain assessments and life cycle assessment (LCA) become prerequisites for building-scale deployment, as seen in Section 4.

3.5 | Negative Effects of Biochar in Energy Storage and Conversion

Biochar materials have been extensively used in many energy conversion and storage applications, as they exhibit a vast structural and morphological diversity, the ability to achieve a desired SSA, tunable surface functionality, and optimum electrical conductivity [192, 193]. Even though biochar materials are popular for electrochemical energy storage/conversion systems such as batteries, supercapacitors, and fuel cells, their usage in other energy technologies such as solar energy conversion, hydrogen production/storage, and thermal energy storage is also getting more attention. Despite the numerous advantages, biochar materials suffer from many drawbacks or challenges, which need to be addressed effectively to strengthen their application potential in electrochemical energy storage and conversion devices.

3.5.1 | Specific Surface Area (SSA)

Pristine forms of biochar (produced from almost all the feedstock) exhibit low SSA, which is undesirable for electrochemical energy storage and conversion applications. In supercapacitor applications, specific capacitances of the fabricated cells are in the range between 5 and 50 F/g. Enhancing the SSA is the only solution to improve the specific capacitance, which can be done via activation. With the benefit of improved SSA, activation processes (either physical or chemical) result in poor yield, which is undesired for scaling activities [194]. Figure 6a shows the significant loss of yield for the synthesis of activated carbon from jatropha oilcake-based biochar. Further activation process also leads to the reduction in nitrogen content as seen in Figure 6b [194]. Furthermore, choosing the right activating method, activators, and activating parameters are essential, which influence the

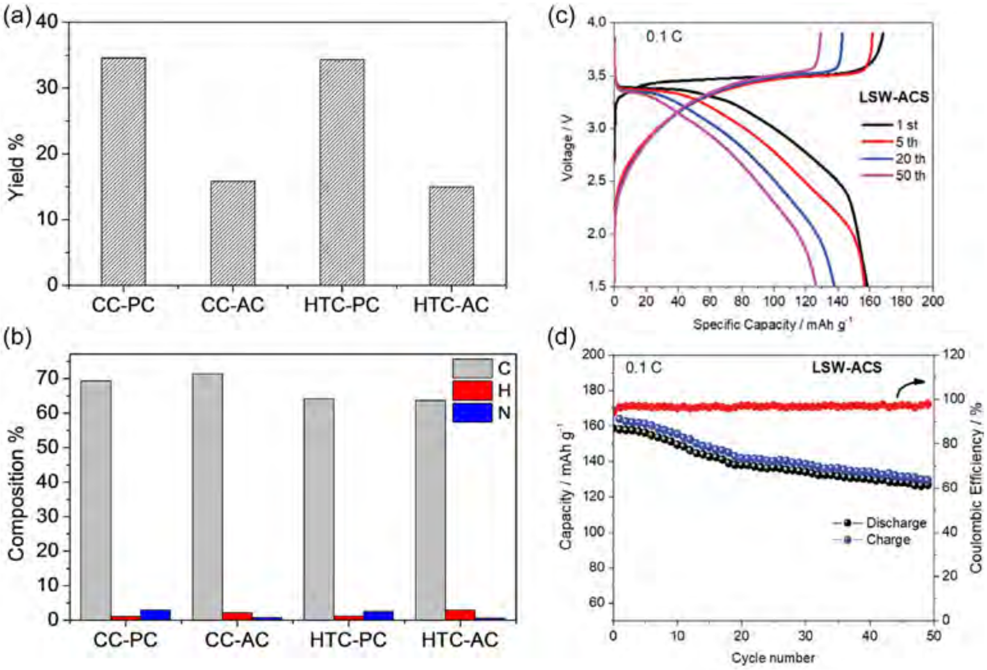

FIGURE 6 | (a) Yield and (b) elemental composition of activated 'biocarbon', that is, biochar, produced from the jatropha oilcake based biochar. Adopted with permission from ref. [194] Copyright 2020, John Wiley and Sons; (c) galvanostatic charge–discharge profile, and (d) cycling behavior of the lithium cell fabricated using the tannery waste activated biochar. Adopted with permission from ref. [195] Copyright 2022, Royal Society of Chemistry.

various physicochemical properties of the biochar products. Creation of more amorphous content in biochar (during the activating process) exhibits poor cycling performance in lithium batteries. Biochar produced at higher temperatures (ca. >1000°C) results in narrow graphitic interlayer spacing, which is ideal for Li ion storage [13]. In order to achieve more graphitic content, a higher processing temperature is essential, which adds additional production cost. It was reported that the cost range of fossil graphite is between \$800 and \$2500 per ton and the production of bio-graphite can exceed \$3000 per ton as it is associated with large energy-intensive processing steps [196]. Additionally, the increasing pyrolysis temperature reduces the porosity, surface functional groups, and the concentration of heteroatoms.

3.5.2 | Impurities and Ash Content

After the pyrolysis process, the major (silica, calcium, potassium, etc.) and minor (sulfur, phosphorus, iron, etc.) minerals present in the biomass remain in biochar as oxides, silicates, carbonates, sulfates, chlorides, and phosphates, which are called ash [197]. In general, most of the biochar materials contain a significant amount of these inorganic impurities/ash, which offer significant and complex impacts (both positive and negative) on the electrochemical performance, in batteries, supercapacitors, and fuel cells. Apart from the positive impact (creation of pseudo sites, maintaining the pH of electrolyte, and possible heteroatom doping), excessive ash content in the biochar causes the lowering of the carbon content and electrical conductivity, and the loss of SSA and pore volume, leading to the internal cell resistance and poor cycling performance of batteries and supercapacitors. Purification via acid etching is essential to remove or minimize these inorganic impurities, which also eliminates some amount of amorphous carbon and creates additional functional groups. These functional groups are reactive with electrolytic constituents and hinder their cycling performance by creating a passive layer. To avoid this, biomass with lower ash content is preferred and a detailed biomass characterization is warranted.

3.5.3 | Electrical Conductivity

The electrical conductivity of biochar is important for the performance of electrochemical energy storage and conversion devices due to their lower charge transfer resistance, higher energy efficiency, and power density. Biochar produced at lower temperatures show poor electrical conductivity, which needs to be enhanced. It can be achieved by increasing the degree of carbonization (which increases the carbon content) by employing higher pyrolysis temperatures, leading to graphitization, which enables efficient electron hopping [34]. Increasing pyrolysis temperature consumes more energy, leading to lower yield, reduced surface functionality, and SSA. Interestingly, catalytic pyrolysis enables the achievement of a better graphitization at relatively lower temperatures but leaves metal impurities. Moreover, the processing parameters vary with different biomass to achieve the desired electrical conductivity for the targeted applications. It was reported that employing the same pyrolysis temperature (1500°C) results in the electrical conductivity of 14,600 and 21,000 S/m, respectively, for wood and bamboo biochar [198]. Thus, optimizing the pyrolysis conditions for each biomass is essential in order to match the physicochemical properties of different biochars, however, it is a challenging task.

3.5.4 | Stability of Biochar

Structural, morphological, and functional stability of biochar products during longterm storage and utilization in various devices (energy storage and conversion) is a major factor for their successful real-world applications. Sorrenti et al. [199] reported that the environmental exposure of biochar leads to increased skeletal density and reduction of water imbibition rate due to partial pore clogging. This also happens when biochar is exposed to electrolytes, which reduces the electro-active sites, decreases the pore volume, and creates passive layers leading to capacitance loss. Amorphous constituent is weaker than its graphitic counterpart and degrades rapidly. During charge/discharge cycles, biochar undergoes significant volume changes and swelling due to the ionic mobility within its structure (insertion/extraction), potentially leading to carbon disintegration, consequently causing a loss in mechanical strength and electrical contact [200]. Salimi et al. [195] reported the specific capacity loss of lithium-ion cell fabricated using tannery waste activated biochar (steam as activating agent) during the different intervals of 1–50 cycles. Figure 6c and d, respectively, show the galvanostatic charge–discharge profile and cycling performance of the lithium-ion cell, which indicate the significant loss of specific capacity (~20%) from its initial value of discharge capacity of 159 mA h g^{-1} [195]. In most of the cases, the high-temperature processing of the biomass leads to the loss of heteroatom functionalities, which is the source for surface hydrophilicity and hampers the electrolyte wettability [13]. Extensive investigation is essential to identify the changes occurring in the biochar during the storage and device performance to manipulate the processing parameters toward desired device performance to compete with conventional carbon materials.

3.5.5 | Challenges Involved in Developing Commercial Products

Although researchers have developed biochar products (graphitized biochar) with comparable or superior properties (electrical conductivity) compared to the commercially available fossil products (conducting carbon), they have not been utilized in commercial devices [48, 201]. Apart from the extensive lab-scale research and relevant publications, the application of engineered biochar in commercial energy storage and conversion devices needs to address more challenges. This includes economic production of biochar products, upscaling the production facilities, reproducibility of various physicochemical properties, optimization of processing conditions, creation of an accessible biochar database, and ensuring the biomass availability. Furthermore, policy support (in terms of financial incentives, tax benefits, and subsidies) is essential to encourage the usage of engineered biochar in commercial products.

3.6 | Negative Effects of Biochar in Hydrogen Storage

Hydrogen is gaining more interest as an energy carrier. Hydrogen produced by electrolysis using renewable energy sources, such as wind, solar, and hydroelectric power; also known as green hydrogen, is foreseen as an important energy carrier in the transition to a more sustainable economy, that is, the green transition [202].

The demand for green hydrogen stems from, for example, the growing fleet of hydrogen fuel cell vehicles and from the transition of iron ore reduction from using conventional blast furnaces with iron ore and coke to direct reduction of the ore using hydrogen in the furnaces. Although hydrogen has the highest heating value per mass, it also has a very low heating value per volume at normal temperature and pressure due to its low density. This means that storage of energy in the form of hydrogen is challenging. The various methods for hydrogen storage are compression (typically to 35–70 MPa), cryogenic storage, chemical storage by conversion to, for example, ammonia, underground storage in large caverns, such as salt or rock caverns, and solid-state storage in the form of metal hydrides [203]. All the methods are associated with various costs in terms of different degrees of energy losses, voluminosity, and equipment/infrastructure investments; as well as fire, explosion, and toxicity risks.

Solid-state storage refers to storing hydrogen in a solid, preferably at normal temperature. The conventional method is by chemically reacting hydrogen with metals to form metal hydrides [204]. This method achieves a high volumetric energy density and is also considered a safe method, although is expensive. The high degree of safety is directly linked to the major drawback of the method, the fact that releasing the hydrogen gas from the storage is complex and requires energy, typically heat. Metal hydrides are also heavy, which makes the method less attractive for vehicles, but still an option for fixed infrastructures, such as, for example, the reduction of iron ore. As an alternative to using metal hydrides for solid-state hydrogen storage, the use of porous carbon materials (e.g., biochar), where the hydrogen molecules are physisorbed on the surface, has been extensively researched. One advantage as compared to using metal hydrides is that the energy required to regain the hydrogen gas is relatively low due to the lower binding energies for physisorbed hydrogen as compared to chemical bonding [205].

Conventional porous carbon often has relatively large amounts of mesopores and macropores with diameters of several nanometers [206]. This implies a relatively low surface-to-volume ratio of the material, which reduces the volumetric storage efficiency by physisorption. Biochar, characterized by its microporous structure with small pore diameters, has therefore attracted attention for hydrogen storage, for example, with feedstock from wood [207], corncob [208], as well as more fundamental studies on cellulose [209]. Studies on thermochemically controlling the pore structure of biochar for hydrogen storage purposes have been undertaken [210] as well as detailed studies of the pore structure and surface area per unit of mass [211]. Despite the aforementioned advantages related to the pore size of biochar, the hydrogen adsorption capacity is low, typically below 1% by weight. Although this is higher than for other types of activated carbon, it is still low for usage as an efficient storage material [205]. This applies to normal temperature (~293 K), and higher capacities can be achieved under high-pressure conditions. However, in order for biochar-based hydrogen storage to be competitive in relation to other methods, it is important that the storage process is simple and cost-effective, where pressurization has a major negative impact on both aspects. Significant enhancement in storage capacity can be obtained with metals, for example, palladium (Pd), incorporated in the biochar [212, 213]. One mechanism for the storage enhancement is the so-called spillover effect, where the hydrogen molecules are catalytically dissociated at the metal sites, which enhances the diffusivity of hydrogen over the surface of the entire porous structure [214]. It has been reported that the hydrogen storage capacity can be increased by 300% using metal sites with Pd, at room temperature [215]. There are, however, several drawbacks of such treatments. Firstly, the requirement of Pd will drive the cost up and make the storage method dependent on a metal with a sensitive supply chain [216]. Secondly, engineering with metal nanoparticles [217] will make the production of the storage system, as well as its operation, more sensitive to environmental parameters, which will add to the general complexity of securing biochar quality due to the feedstock and production dependencies that were mentioned in the introduction of this article. Further research should include optimized cost-effective functionalization along with a tailored porous structure. The production method must be scalable and robust, which is a significant challenge for the biochar research community.

3.7 | Negative Effects of Biochar in Soil/Environment

Biochar is a relatively new member of the big carbonaceous material family. Unlike activated carbon, biochar is not usually subjected to very high temperatures (ca. > 800°C), steam, and/or chemical agent treatments after carbonization. In most studies, biochar is not activated, so its surface chemistry and structure are not further modified and stabilized after pyrolysis. For example, the free radicals generated on the biochar surface [218] during pyrolysis are stable for more than a month [219] if biochar is not exposed to ambient air, where molecular oxygen can be chemisrobed [220] and consume the free radicals. Although its beneficial effects as a soil amendment are well known, biochar can induce negative redox responses in soil, including but not limited to arsenopyrite weathering and heavy metal release [221, 222] germination inhibition, and suppressed plant/crop growth [219], and toxicity to soil microorganisms [218]. This section critically reviews the literature for negative effects of chemical/elemental ‘hotspots’ induced by biochar, whereas the biochar’s (negative) effects on soil biota are not covered here, since those have been covered extensively by Lehmann et al. [223]. Other researchers have also reviewed biochar ecotoxicology [224], biochar structural/chemical evolution and risk in soil and water [225], and overall hazards in soil, aqueous, and atmospheric environments [21].

When biochar is applied in soil or aqueous environments, the instability (relative to granular activated carbon) of its physical and chemical properties, exacerbated by environmental conditions (pH, ionic strength, temperature, effects of microorganisms, etc.), makes it a localized source for elemental release. If no mitigation measures precede, biochar might become a new source of contamination, (slowly) releasing dust (i.e., PM_{10} aerosols: particles $< 10\ \mu m$) [226], dioxins [227], polycyclic aromatic hydrocarbons (PAH) [227, 228], heavy metals such as copper, nickel, zinc, lead, chromium, cadmium, and arsenic [229, 230], excessive nutrients such as inorganic nitrogen and phosphorus [231], undesirable levels of magnesium [232], dissolved organic matter (DOM) [233, 234], micropollutants [235, 236], and colloidal and dissolved black carbon (facilitating contaminant transport) [237].

Emerging contaminants, such as per- and polyfluoroalkyl substances (PFAS), have also been detected in activated sludge-derived biochar [235, 236, 238]. However, the bioavailability and/or leachability of such PFAS remain largely unknown. PFAS that are detected in activated sludge include long-chain and more hydrophobic PFAS, which tend to partition into the solid phase (instead of the aqueous phase) during wastewater treatment [239–241]. When considering the use of sludge-based biochar as a soil amendment, it is critical to monitor PFAS levels in the wastewater treatment plant, the source of the sludge, at different stages of treatment, test PFAS residuals on the resulting biochar, and select appropriate PFAS decontamination strategies for the resulting biochar. It is further advisable to monitor PFAS levels in soil after application of sludge-derived biochar to prevent such biochars from becoming a continuous source of pollution to soil and groundwater [235].

As a soil amendment, biochar's potential as a carbon sink can influence the global carbon cycle. It is considered a negative-emission technology by sequestering otherwise biodegradable carbon into functionalized materials for agricultural and environmental applications [242–244], assuming biochar can be imparted with high stability and chemical recalcitrance. However, depending on the application setting, applied rate (biochar to soil weight ratio), and environmental conditions, biochar might become a carbon source as it ages [245], through its chemical and microbial decomposition [246, 247], and via physical weathering [248]. A model predicted that biochar carbon losses were 3%–26% after use for 100 years, with carbon half-lives ranging from 10^2–10^7 years [247], and a 5-year laboratory experiment showcased that 0.5%–8.9% of the biochar carbon was mineralized [249]. Physical weathering appears to be a significant factor contributing to carbon loss from biochar as shown by a study using a 24-h artificial weathering (biochar-water suspension shaking in a batch reactor), which led to graphitic sheet expansion, structural cracking and fracturing, and disintegration of biochar, accounting for 1%–47% mass loss [248].

The release of dissolved organic carbon (DOC) from biochar into soil can alter microbial activity, nutrient cycling, and even water quality by mobilizing labile carbon fractions. Moreover, leached carbon species may interact with cocontaminants or nutrients in complex ways, either enhancing or inhibiting their mobility and bioavailability. In addition, weathering can release airborne carbon particles. Biochar dust, for example, released through the abrasion of larger biochar particles into PM_{10} aerosols [226], causes an inflammatory condition and oxidative stress in living organisms, as demonstrated recently through in vitro and in vivo studies [250].

Notably, the long-term carbon budget would be affected by colloidal biochar particles [237] and DOM [251] released from bulk biochar. For example, compared to the bulk, its water-dissolved fraction, DOM, has a higher polarity with more functional groups, smaller fused aromatic clusters, and lower aromaticity. Thus, it is more chemically reactive and less recalcitrant than bulk biochar [237]. In addition, biochar colloids can be co-transported with plastic particles. A study demonstrated such co-transportation of colloidal biochar particles (0.6–1 μm) with plastic particles in a flow-through column study. The mechanism is larger steric repulsion to the column porous media compared to the control, and the mobility of biochar was higher in the presence of either nanoplastics (0.02 μm) or microplastics (0.2 μm) [252].

Biochar-induced pH increases would dissolve more DOM from biochar. For example, blending biochar in soil at a high rate (10 wt.%) increased soil pH from 4.9 to 8.7, and the resulting higher pH was shown to desorb and dissolve soil mineral-bound DOM [234]. Similarly, the content of base-extractable DOC in biochar was found to be higher than that of acid-extractable DOC, whereas extractable DOC content decreased exponentially with pyrolysis temperature increasing from 300°C to 600°C [251]. A large fraction of molecules in base-extractable DOC precipitated at acidic pH due to high molecular weight and aromaticity [251].

Thus, investigators need to further research the resulting dynamic carbon flux in soil and aqueous environments to recalculate the carbon budget after biochar application. For instance, kaolinite, a widely used soil mineral, enhanced the stability of the dissolved fraction of biochar through metal bridging, ligand exchange, and van der Waals attraction [253]. Researchers should also investigate more environmentally friendly manufacturing strategies to ensure biochar is a pollutant remediation medium and not a source. For example, brief, moderate-temperature air thermal oxidation (400°C for 20 min) in a regular muffle furnace effectively abated PAH residues (up to 85% Tot-PAH) in biochars, decreasing the U.S. EPA Relative Potency Factor by up to 82% [254]. Understanding the potential negative impacts of biochar on soil, such as carbon leaching, contaminant release, and unintended ecological effects, is essential for designing biochars that are both environmentally safe and effective for long-term carbon sequestration and pollutant mitigation.

4 | Negative Effects of Biochar Observed through LCA Analysis

LCA is widely applied as a systematic and standardized method for evaluating the environmental impacts of materials and processes across their entire life cycles [255, 256]. In particular, numerous studies, including case-specific assessments, have examined the climate-related effects of biochar, with a focus on its production pathways and comparisons with alternative technologies [21, 257, 258]. While the majority of these studies report favorable environmental and material performance outcomes by use of biochar, potential negative impacts must also be critically considered. A variety of environmental indicators, such as net GHG emissions, global warming potential, sensitivity indices, and nitrogen and phosphorus efficiency coefficients, have been employed to comprehensively assess the environmental implications of biochar [259–262]. Some biochar production systems, particularly low-technology kilns commonly used in certain tropical regions, have been associated with high emissions of gases and aerosols during pyrolysis due to limited emission control, resulting in negative environmental impacts and reduced net carbon sequestration benefits. This results in significant negative environmental impacts and limited benefits in terms of carbon sequestration [263, 264]. The emissions from biochar systems include CO_2, CO, CH_4, N_2O, and particulate matter, whose yields are governed by reactor type, pyrolysis temperature, residence time, and the extent of oxygen limitation during thermo-chemical conversion process. Systems employing modern, controlled reactors with syngas capture and combustion for process heat generally have low net GHG emissions compared to traditional low- technology kilns lacking a proper emission control. Furthermore, the utilization of coproducts, such as bio-oil and syngas for energy recovery, can highly improve the overall carbon balance and environmental performance of biochar production systems. Matuštík et al. [257] demonstrated that while advanced low-emission pyrolysis facilities can improve the sustainability of biochar by enabling energy cogeneration, regions with limited access to such technologies often rely on fossil fuels, which undermines the environmental benefits and may even exacerbate the overall environmental footprint of biochar systems. Research on the potential adverse environmental impacts of biochar systems remains limited. Further studies employing standardized LCA methodologies and consistent assumptions are needed to more accurately evaluate the true environmental performance of biochar systems.

5 | Conclusions

This review article has analyzed the unintended consequences of biochar in various applications such as polymer composites, building materials, energy storage and conversion, soil, and environmental applications. Although favorable effects of biochar have been reported in different applications, it may exhibit some undesirable effects if its properties are not effectively engineered. Biochar made from two different biomass or different pyrolysis processes can have significantly different properties related to SSA, carbon/ash content, and so on. These variations in properties can manifest as problems in products, since maintaining consistent quality would be challenging. Biochar also has a tendency to self-ignite, and its dust cloud can explode, which should be subjected to risk assessment in industries (e.g., steel industries) where storage and handling of large amounts of biochar are prevalent. For the use of biochar in polymeric composites, the biggest negative effect is the lowering of tensile strength (or no improvement in the strength). When biochar is used to impart fire-safety in composites, it mainly acts as a non-combustible (depending on the way the biochar was made) additive without contributing to fire retarding effects through gas or condensed phase reactions. When the use of biochar in concrete is considered, the biggest negative effect is the lowering of workability of the concrete mix. In addition, biochar application for energy storage and conversion requires higher SSA, which can be achieved only via an activation processthat lowers overall biochar yield, electrical conductivity and structural stability. Balancing the various desired properties for biochar materials is more complicated, especially for energy applications. For applications of hydrogen storage, the adsorption capacity of biochar is low, and for soil/environmental applications, the complexity of the system makes introducing biochar potentially harmful since DOC from biochar can be introduced into soils, leading to the alteration of the microbial activity, nutrient cycling, and even water quality. Although a renewable material itself, biochar maybe not always have positive environmental effects as observed through LCA studies. In summary, it is critical to be aware of the potential negative impacts of biochar in different applications and comprehend the reasons behind them. Only then, researchers would be able to engineer and tailor biochar production and characteristics to circumvent the occurrence of undesirable outcomes and amplify the desirable properties of biochar-added materials and products.

Author Contributions

Oisik Das: conceptualisation, writing – original draft, writing – review and editing, visualisation, validation, supervision. **Singaravelu Vivekanandhan**: conceptualisation, writing – original draft, writing – review and editing; visualisation; validation. **Dong Wang, Vigneshwaran Shanmugam, Aurelio Bifulco, Elif Kaynak, Julio Diarte Almada, Imelda Saran Piri, Zhengyang Wang, Lokesh Padhye, Nam Kyeun Kim, Michael Försth, Jaime Gonzalez-Libreros, Igor Wachter, and Sabrina Karim**: writing – original draft, writing – review and editing, visualisation. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets used or analysed during the current study are available from the corresponding authors upon reasonable request.

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