Tao *et al. Environmental Sciences Europe* *(2024) 36:79*
https://doi.org/10.1186/s12302-024-00908-7

Environmental Sciences Europe

REVIEW **Open Access**

Utilization of cotton byproduct-derived biochar: a review on soil remediation and carbon sequestration

Yingru Tao[1], Weiying Feng[1*], Zhongqi He[2*], Beibei Wang[3], Fang Yang[4], Aainaa Izyan Nafsun[5] and Yazhai Zhang[5,6]

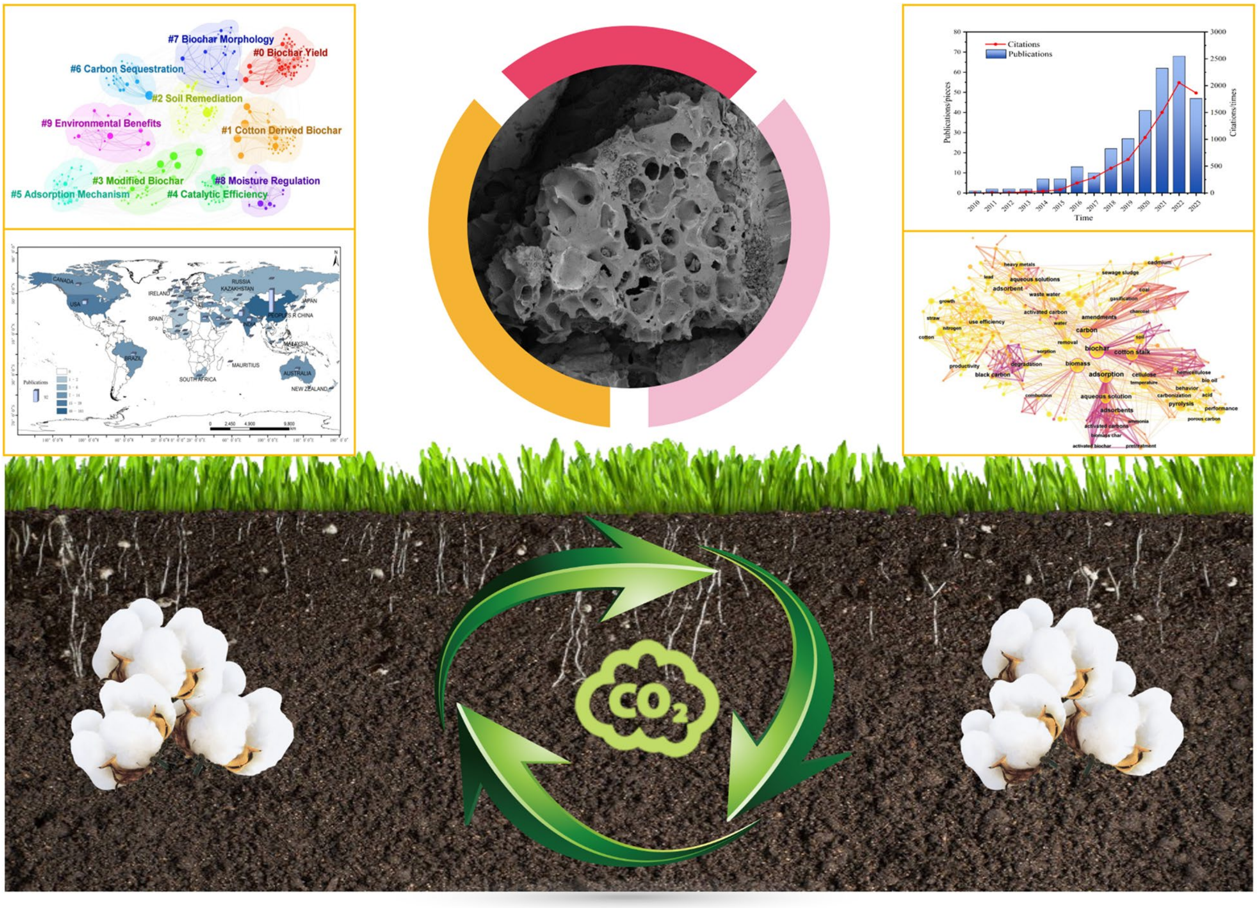
Abstract

Biochar can improve soil health and fix CO_2 by altering soil microenvironment, thus impacting the global carbon cycle and the change of soil ecological environment. Recent studies show that cotton byproduct-derived biochar is a potential effective amendment for soil improvement so that it could play an important role in agricultural and environmental conservation. In this work, research topics on cotton byproduct-derived biochar in soil in last decade and so are systematically reviewed for better understanding of the progresses of cotton byproduct-derived biochar in (i) the morphologic and physicochemical characterization, (ii) latest research hotspots and trends, (iii) the roles in soil reclamation, and (iv) relevant carbon sequestration mechanisms. Finally, the future research directions regarding cotton byproduct-derived biochar mingled to soil environment are discussed. Insight derived from this work would provide scientific basis for promoting more applications of cotton byproduct-derived biochar in soil ecological restoration and carbon fixation.

Keywords Cotton, Biochar, Soil remediation, Carbon sequestration, Byproducts

*Correspondence:
Weiying Feng
fengweiying@buaa.edu.cn
Zhongqi He
Zhongqi.he@usda.gov
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Biochar, a recalcitrant, carbon (C)-enriched solid product from the pyrolytic treatment of biomass materials, has demonstrated a promising soil amendment for enhancing soil health, carbon sequestration, and contamination remediation [1–3]. Globally, natural soil is the largest terrestrial carbon pool, sequestering more than 3.5×10^{12} tons of carbon in the form of soil organic matter. The amount of carbon stored in soil is approximately three times of that found in the atmosphere (primarily as CO_2) and five times of that preserved in all the terrestrial plants [4]. Soil carbon sequestration is recognized as an essential and effective method within the broad spectrum of climate change mitigation strategies [5]. In response, a recent global initiative has set an ambitious objective to annually increase the global soil organic matter content by 0.4%, a measure that significantly contributes to mitigating greenhouse gas emissions [6]. Therefore, in the face of increasingly serious global issues such as climate change, environmental pollution, and soil erosion, using biochar for soil remediation and carbon sequestration presents a highly promising approach [7–11]. Since 2010, there has been a rapid increase in the publication of biochar research [12]. Over this time and in trial bases, biochar has been extensively used in various. The main areas of research focus on biochar production [13], its impact on global climate change [14], soil quality and plant growth [15], organic pollutant removal [16], and heavy metal immobilization [17]. More recently, biochar has gained special attention for composting organic solid waste [18–20]. Additionally, research has also been on improved pyrolytic reactors such as microwave reactors, fixed-bed reactors, screw-feeding reactors, bubbling fluidized bed reactors, and technologies like solar pyrolysis, the Thermo-Catalytic Reforming process, and liquefaction technology. These are being extensively studied for their efficiency in energy production and the modification of biochar for environmental remediation [21].

Cotton (*Gossypium* spp.) is a global crop grown primarily for fiber used in the textile industry [22]. In addition to the target product fiber, cotton production also results in a number of biomass byproducts including cotton stalk, cotton husks, cotton gin waste (trash), cottonseed, cottonseed hulls, and cottonseed meal [23–26]. Cotton byproduct-derived biochar has several advantages, including increased crop yields and reduced fertilizer requirements [27], soil carbon sequestration [28], and soil remediation [29]. Recent studies have led to the development of a porous and multifunctional biochar from medical waste cotton using an acid–base modification method [30]. Adding the biochar into an acrylate-based hydrogel through free radical polymerization created a composite material featuring chitosan and ethylenediaminetetraacetic acid (CS/EDTA/CBC). This technique enhanced both the adsorption capacity of cotton waste-derived biochar and the structural stability of the hydrogel. Studies have shown that this composite material is highly effective in adsorbing pollutants like Pb^{2+}, Cu^{2+}, and methylene blue, outperforming many known adsorbents [30]. Moreover, research on applying biochar made from cotton waste to cotton fabrics has revealed that this method improves fabric performance, enhances moisture transfer and drying properties, and effectively masks odors [31]. This innovative method demonstrates a sustainable way to recycle cotton waste. So far substantial research has been conducted to develop functional biochars from cotton byproducts and assess the potentials of cotton byproducts-derived biochar as a soil amendment for enhancing carbon sequestration and soil contamination remediation. This article aims to review the related research findings and provide guidelines for better valorizing cotton byproducts through specialty biochar development.

This review focuses on cotton byproduct-derived biochar and its efficacy on soil remediation and carbon sequestration for agricultural and environmental applications. Four aspects were highlighted: (i) surface morphology and physicochemical characteristics of cotton byproduct-derived biochars, (ii) research hotspots and development trends of cotton byproduct-derived biochar products in recent years, (iii) the roles of cotton byproducts-derived biochar in soil reclamation, and (iv) the mechanisms of cotton byproduct-derived biochar for facilitating soil carbon sequestration. Future research directions regarding cotton byproduct-derived biochar in soil environments were also outlooked.

Data acquisition and methods

CiteSpace (Version 6.2) was used to procure the literature information. The software, renowned for uncovering emerging trends in scientific research, encompasses a broad spectrum of functions, such as analyzing cooperation networks across authors, institutions, or countries, examining the co-occurrence of keywords or Web of Science categories, and delving into co-citation analysis of both literature and authors [32, 33].

A total of 311 scientific articles were retrieved from the Web of Science (WOS) Core Collection. The search topic was "Cotton stalk biochar OR Cotton seed biochar OR Cotton derived biochar OR Cotton based biochar OR Cotton waste biochar OR Cotton residue biochar". The data were considered valid if it appears in the following three fields including abstract, keywords, and the title of a downloaded record.

Characteristics and hotspot analysis of cotton byproduct-derived biochar

The earliest study on cotton byproduct-derived biochar was published in 2010. This research confirmed that soil amendment with cotton stalk-derived biochar may be applied as an in situ remediation technique to minimize pesticide residues in agricultural produce from contaminated soils [34]. As shown in Fig. 1, the number of publications and citations retrieved from the WOS core collection exhibited a rapid growth from 2010 to 2023. The total number of publications on cotton byproduct-derived biochar increased from only one in 2010 to 68 in 2022. This increase corresponds to the rising interest in biochar as a research subject in the scientific community, a trend further highlighted by the total citations reaching 2056 in 2022 [21].

According to the analysis of WOS search results, research on the cotton byproducts-derived biochar is distributed in 55 countries or regions. Cotton is a cash crop globally cultivated, with four main cultivated species including *Gossypium herbaceum*, *Gossypium arboreum*, *Gossypium hirsutum*, and *Gossypium barbadense* [35]. As shown in Fig. 2, China has published 179 papers, ranking first in terms of publication volume, accounting for 57.56% of the total publication volume, indicating that China played a significant role in cotton byproduct-derived biochar research. That might be attributed to the fact that China is a large agricultural country, where agriculture has an important and strategic position [36]. In 2018, China's cotton yield reached 6.013 million tons, generating a direct annual revenue of 9.574 billion Chinese yuan (~ US$1.5 billion) [37]. Research indicates that, based on the STIRPAT model's predictions, China's cotton production could reduce nitrogen emissions by as much as 54,430 metric tons by 2050 compared to 2018

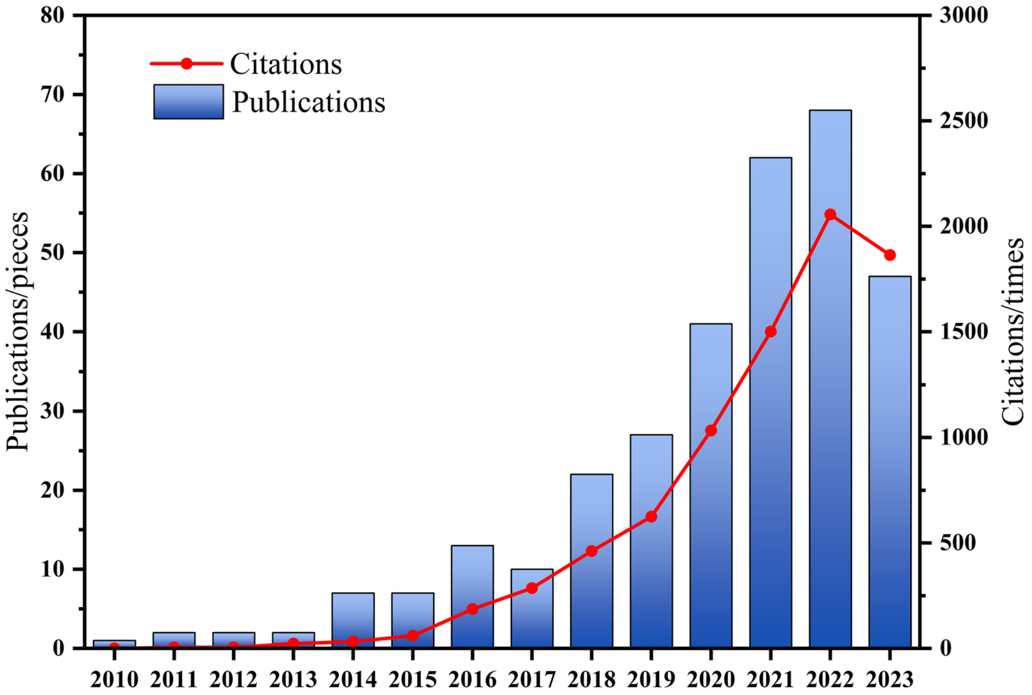


Fig. 1 Citations and publications of articles on cotton byproduct-derived biochar from 2010 to 2023

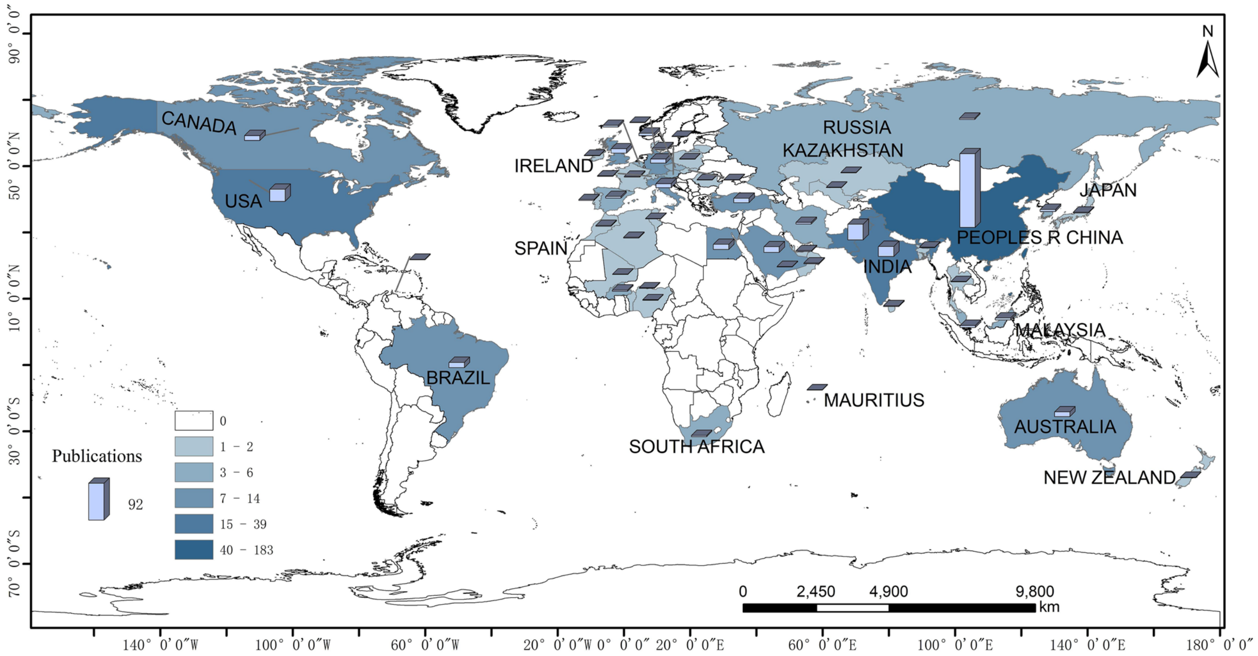


Fig. 2 World map of publication volume by country

levels, reducing fertilizer input and improving fertilizer utilization are the main measures for China's cotton to achieve low nitrogen production [38]. Pakistan secures the second position with 39 publications, constituting 12.54% of the total publication volume. The USA follows closely behind in third place with 30 publications, contributing 9.65% to the overall publication volume. India, Saudi Arabia, Brazil, Egypt, Australia, Canada, Turkey, and others followed.

China has played an important role in the cooperation network and has close cooperation most with other countries. By comparing intermediary centrality, it is found that China (centrality of 0.72) ranks highest in centrality, followed by Pakistan (centrality of 0.41), the USA (centrality of 0.27), indicating that these countries have made significant contributions to research in this field.

There were 311 articles published about cotton byproduct-derived biochar during 2010–2023. Figure 3 describes the network of the main keywords. Some nodes have purple rings around their outer edge indicating the high betweenness centrality of this field. Based on the analysis of the literature, the frequent occurrence of these keywords highlights significant trends and focal points in current environmental science research. In the network map of cotton byproduct-derived biochar, the five most frequently occurring terms in descending order are biochar, biomass, adsorption, cotton stalk, and carbon.

The term "biochar" is an abbreviation of "biochar coal" and was officially coined and adopted at the first International Biochar Conference held in Australia in 2007 [21]. Biomass represents a renewable resource that is gaining attention for its potential to be transformed into value-added products, especially for reducing reliance on fossil fuels and promoting a circular economy [39]. Adsorption technology is pivotal for purifying water and soil by removing toxic heavy metals and organic pollutants. The extensive research into adsorption reflects a continuous demand for improving the efficiency of adsorbents and for developing new materials [27, 40]. Cotton stalk, as an abundant agricultural waste, are being researched for conversion into biochar, indicating an exploration into value-added utilization of agricultural byproducts [41]. Carbon, due to its superior adsorption capacity, making it central to environmental engineering applications [8].

Figures 4 and 5 show a clustering knowledge graph based on keyword co-occurrence, with the clustering algorithm being Log-likelihood rate (LLR). The clusters identified within the field delineate key directions of research. Cluster #1 "Cotton byproduct-derived Biochar" and Cluster #0 "Biochar Yield" underscore the focus on the sources and production of biochar. Cluster #2 "Soil Remediation" demonstrates the application of biochar in soil health and restoration, while Clusters #3 "Modified Biochar" and #5 "Adsorption Mechanism" reflect researchers' efforts to enhance the functionality of biochar, particularly its adsorptive capacity and catalytic

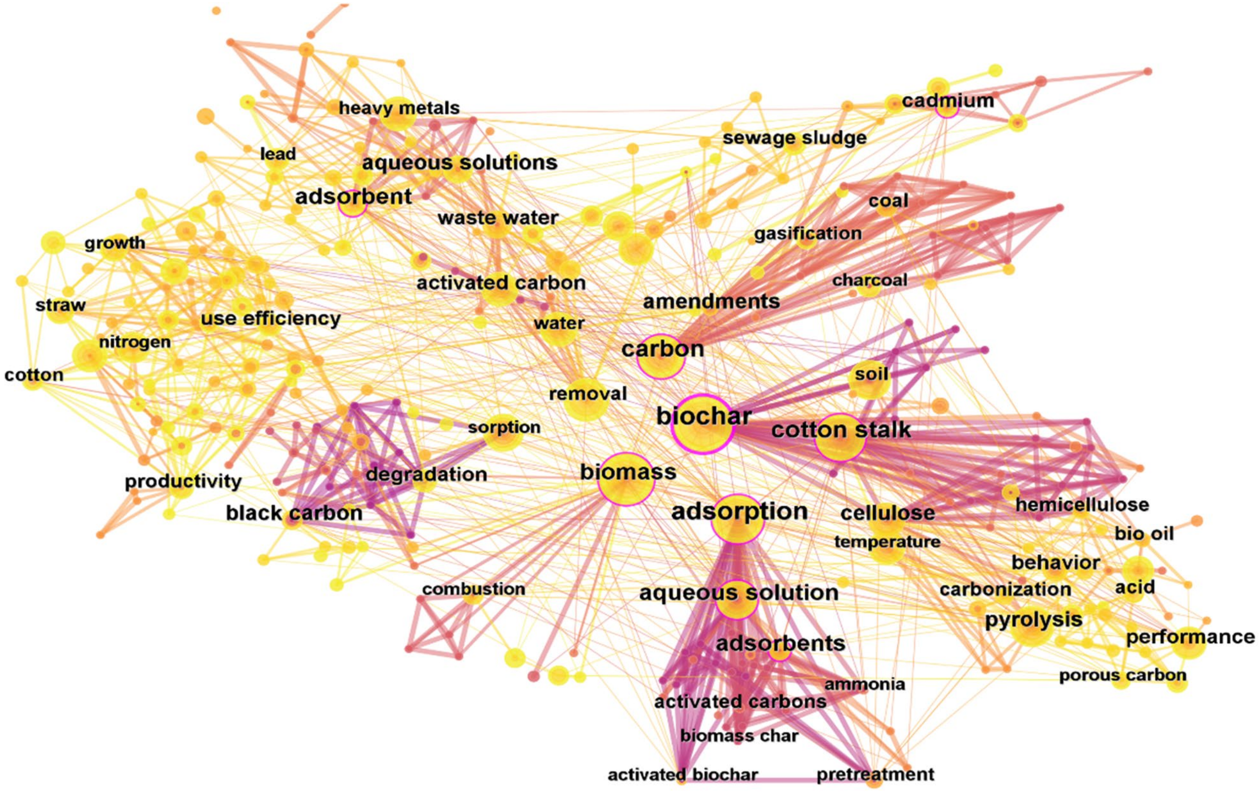


Fig. 3 Network map of cotton byproduct-derived biochar research during 2010–2023

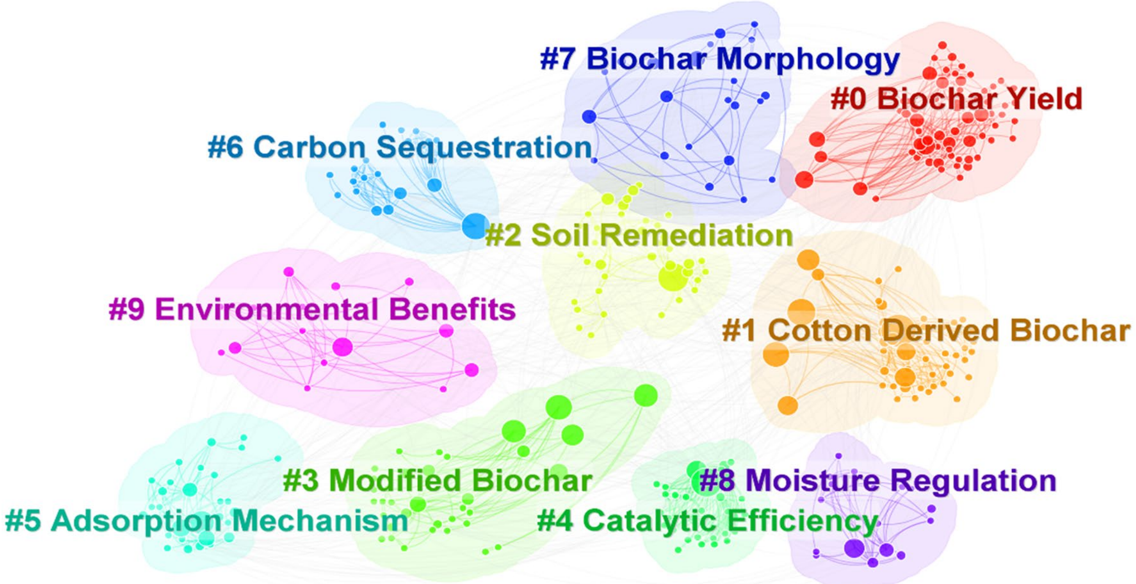


Fig. 4 Co-occurrence clustering network of literature keywords from 2010 to 2023

roles as indicated by Cluster #4 "Catalytic Efficiency". Cluster #6 "Carbon Sequestration" and #9 "Environmental Benefits" highlight the potential of biochar in contributing to climate change mitigation, especially in its relevance to the carbon cycle and the reduction of greenhouse gas emissions. Cluster #7 "Biochar Morphology" emphasizes the importance of investigating the physical properties of biochar, crucial for its application in environmental management. Cluster #8 "Moisture Regulation" suggests the practical value of biochar in managing soil moisture and its use in agricultural applications. In summary, the keyword clustering map not only

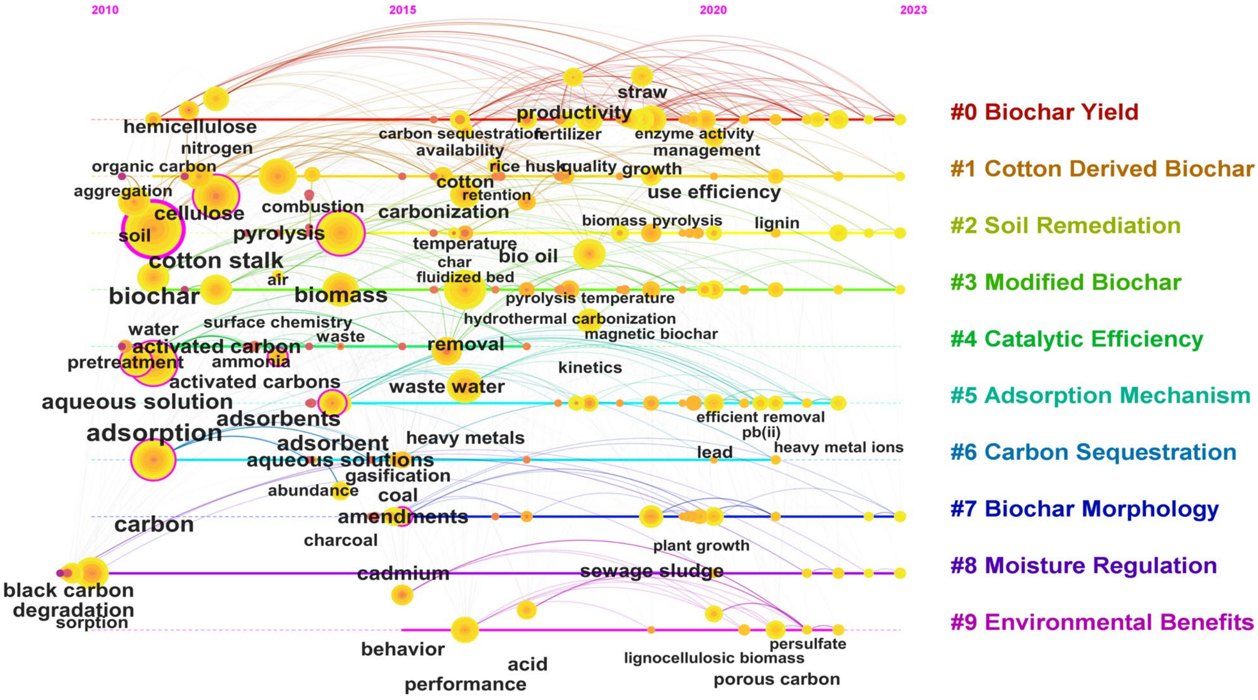


Fig. 5 Co-occurrence timeline of literature keywords from 2010 to 2023

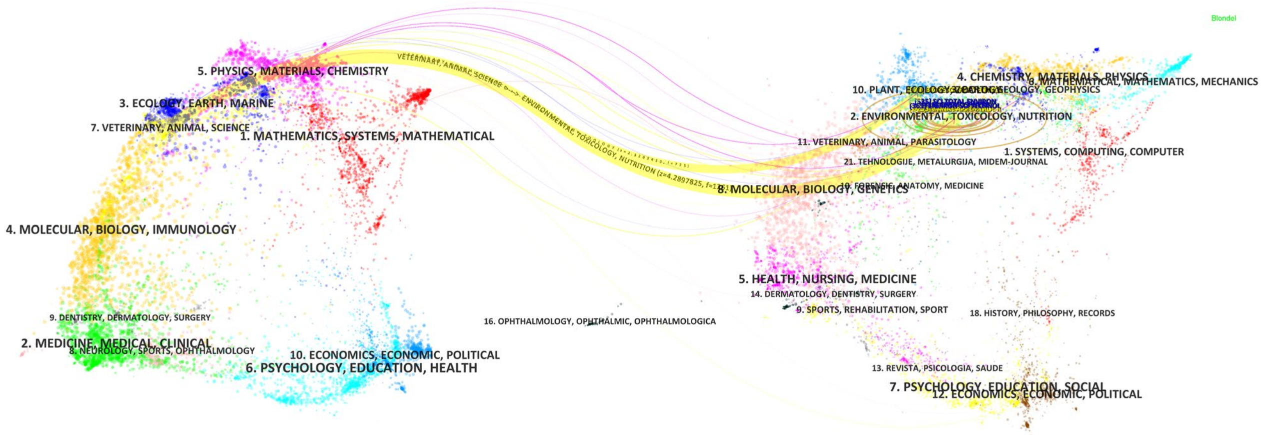


Fig. 6 Double-map superposition of documents

demonstrates the multidisciplinary nature of biochar research but also accentuates its potential applications in the domain of environmental science and engineering.

Discipline correlation analysis is a crucial step in correlating cited literature with the appropriate discipline. This process not only facilitates the identification of the development trajectory of a discipline but also enables scholars to comprehensively comprehend the citation patterns [42]. The double-map overlay presented in Fig. 6, generated using CiteSpace, demonstrates the interdisciplinary nature of biochar research, particularly showing strong connections between various scientific disciplines. In this image, prominent citation pathways from journals in disciplines such as "Veterinary, Animal, Science" and "Ecology, Earth, Marine" to foundational research in "Environmental, Toxicology, Nutrition" and "Molecular, Biology, Genetics" are evident. This indicates a rich exchange of knowledge across these fields, reflecting the role of biochar in bridging environmental strategies with the biological and chemical sciences.

Cotton byproduct-derived biochar surface morphology

Analysis of the morphology of cotton byproduct-derived biochar

Pyrolysis is a thermochemical processing technique used predominantly to convert biomass byproducts into biochar. Typically, slow pyrolysis yields more biochar, while fast pyrolysis generates more pyrolysis bio-oil as the target product [43, 44]. In addition to the modes of pyrolysis, temperature is also a key factor influencing the yield and physicochemical properties of the biochar products [45, 46]. Studies have shown that the morphological characteristics of cotton byproduct-derived biochar play a crucial role in determining its functionality across a range of applications, such as soil health enhancement, pollutant removal, and carbon sequestration [47]. Researchers have found that the porosity and the specific surface area are vital attributes determining the effectiveness of biochar for achieving environmental benefits. The porous structure of cotton stalk biochar, as identified by scanning electron microscopy (SEM) techniques, enhances its adsorption capacity for gases and molecular contaminants [48]. Further studies using SEM techniques have revealed detailed information about the internal structure of cotton byproducts-derived cotton, including the identification of micro and macropores crucial for its functionality. The distribution and size of these pores, along with the surface roughness, significantly impact the adsorption efficiency of biochar in specific applications [49]. For instance, in soil amendment, the microstructure of biochar influences its interaction with soil microbes and plant roots, affecting its efficacy on enhancing soil health [50]. Additionally, SEM combined with Energy-Dispersive X-ray Spectroscopy (EDX) provides a comprehensive understanding of the elemental composition of cotton byproducts-derived biochar. This analysis is crucial for assessing its suitability in applications like heavy metal adsorption from contaminated soils or in improving soil nutrients [51]. In conclusion, understanding the intricate morphology of cotton byproduct-derived biochar through SEM analysis is fundamental to optimizing its application in environmental and agricultural settings. The insights gained from these studies underscore the material's versatility and potential in sustainable environmental practices.

The morphological characteristics of cotton byproducts-derived biochar have profound implications for its applications in both environmental and agricultural fields. A recent study demonstrated the efficacy of cotton byproduct-derived biochar for soil remediation, linking its success to its unique morphological traits [52]. The study emphasizes the importance of porous structure of biochar, surface area, and chemical composition in enhancing soil fertility and structure, as well as in its capacity to adsorb pollutants. The high surface area and porosity of biochar make it an excellent material for capturing and storing atmospheric carbon, thus contributing significantly to mitigating the impacts of climate change. This study highlights the role of biochar in sustainable environmental practices, showcasing its versatility in addressing both soil health and carbon storage challenges. Furthermore, the application of biochar in agriculture extends beyond soil amendment. Studies have shown that biochar can improve water retention, nutrient availability, and even serve as a habitat for beneficial soil microorganisms [53, 54]. These attributes, as revealed through SEM analysis, contribute to the ability of biochar to promote plant growth and increase crop yields. The illustration demonstrates how the physical and chemical properties of biochar, tailored through specific production processes, can be optimized to meet the diverse needs of agricultural applications [26].

Analysis of the morphology of cottonseed biochar

Mill-scale produced cottonseed meal was provided by Cotton, Inc. (Cary, NC, USA) and was used as the biomass material for pyrolysis. The cottonseed meal was converted to biochar and bio-oil using a custom-made benchtop pyrolyzer consisting of a furnace, a pyrolysis reactor (a 3.78-L iron container with a side vent and movable lid), a condenser, and a bio-oil collector. For the conversion of cottonseed meal to biochar, a slow pyrolysis process was utilized, achieving a peak temperature of 600 °C [55].

Figure 7 shows a sample of cottonseed meal that has not undergone high-temperature pyrolysis, featuring distinct fibers and shell-like substances. However, there is an absence of micro-pores or striated structures typical of biochar, and no surface fragmentation is observed. Figure 8 presents a biochar derived from the cottonseed meal through 600 °C slow pyrolysis, where dense pore channels with a diameter of approximately 50 μm are clearly visible in both cross-section and profile views, with notable surface fragmentation in some areas.

The cottonseed meal samples distinctly exhibit the original microstructure of the biomass. As they have not been subjected to pyrolytic degradation, their surfaces are predominantly rough and dense biomass shells

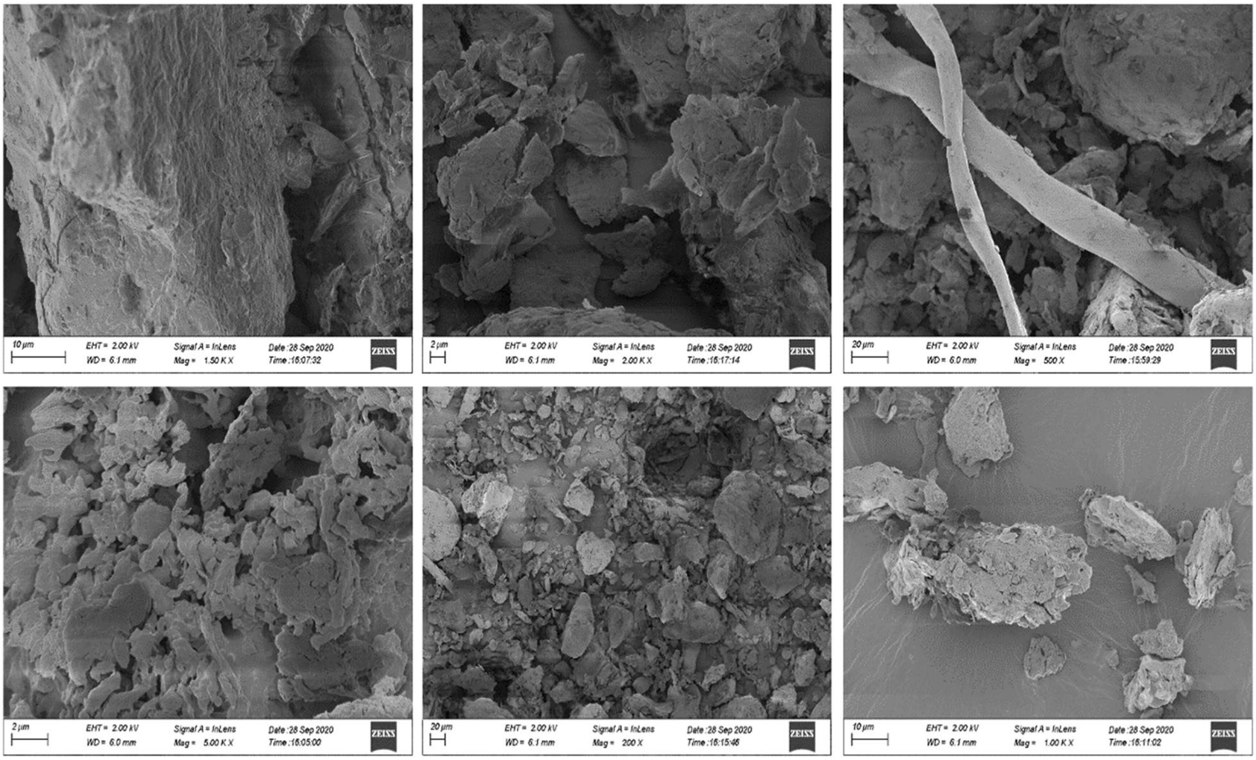


Fig. 7 SEM images of defatted cottonseed meal powder (Feng et al. unpublished data). Refer to Ref. [55] for the composition information of the meal sample

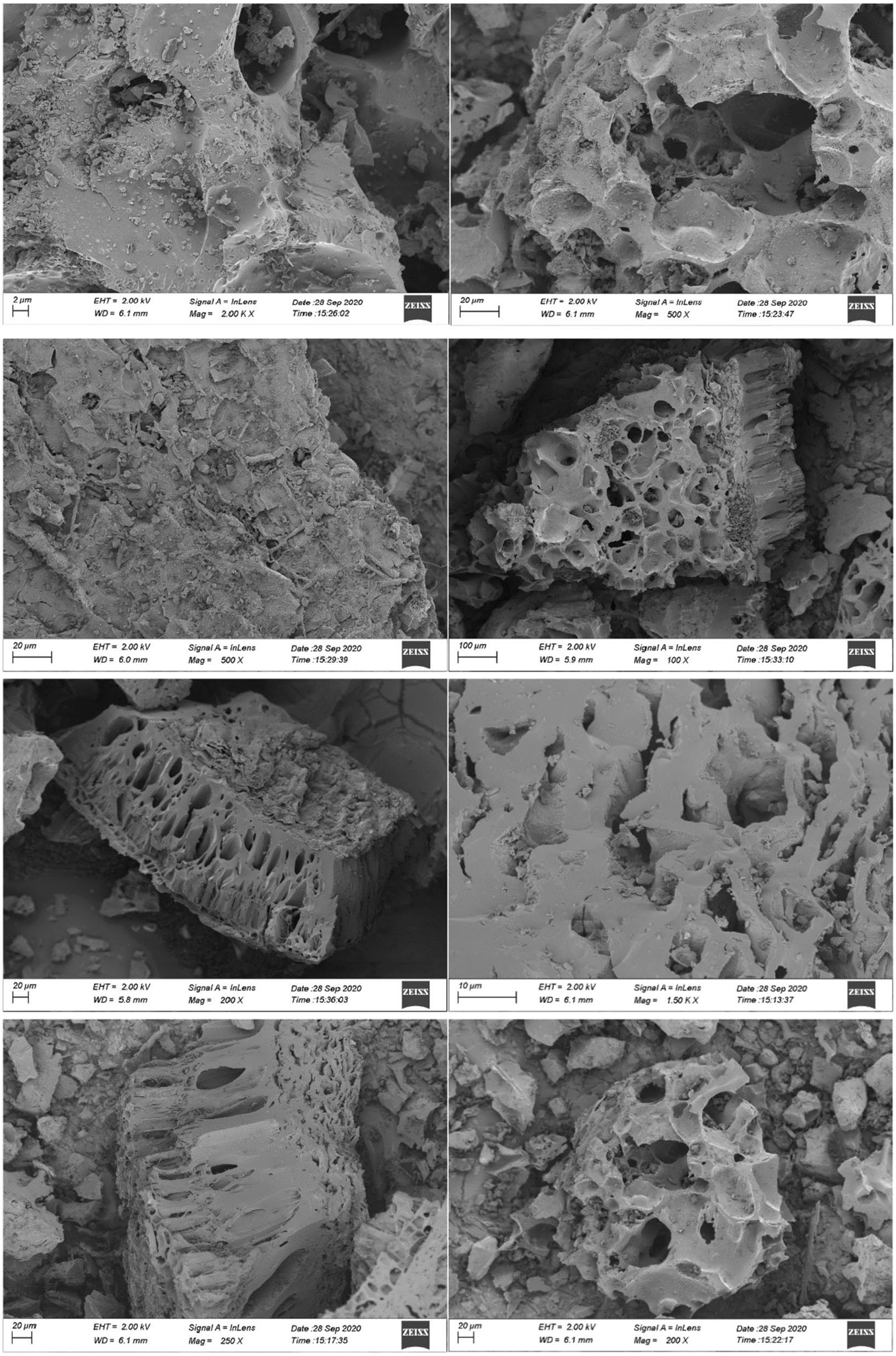


Fig. 8 SEM image of defatted cottonseed meal biochar products (Feng et al. unpublished data). Refer to Refs. [58, 59] for the preparation of these biochar products

Table 1 Physicochemical properties of cotton byproduct-derived biochar at different pyrolysis temperatures

Biochar type	Pyrolysis temperature (°C)	Yield (%)	Elemental analysis (%)					Atomic ration (%)		S_{BET} (m^2/g)	References
			[C]	[H]	[O]	[N]	[S]	H/C	O/C		
Cottonseed Hull Biochar	200	83.4 ± 0.8	51.9 ± 0.5	6.0 ± 0.1	40.5 ± 0.4	0.60 ± 0.04	0.99 ± 0.01	1.38 ± 0.02	0.59 ± 0.01	n.d	[65]
Cottonseed Hull Biochar	350	36.8 ± 0.1	77 ± 1	4.53 ± 0.05	15.70 ± 0.04	1.9 ± 0.4	0.8 ± 0.1	0.70 ± 0.01	0.153 ± 0.001	4.7 ± 0.8	
Cottonseed Hull Biochar	500	28.9 ± 0.1	87.5 ± 0.1	2.82 ± 0.02	7.6 ± 0.2	1.5 ± 0.1	0.50 ± 0.01	0.385 ± 0.003	0.065 ± 0.002	0	
Cottonseed Hull Biochar	650	25.4 ± 0.2	91.0 ± 0.4	1.26 ± 0.02	5.9 ± 0.3	1.6 ± 0.1	0.26 ± 0.03	0.166 ± 0.002	0.049 ± 0.003	34 ± 3	
Cottonseed Hull Biochar	800	24.2 ± 0.6	90 ± 1	0.6 ± 0.1	7 ± 1	1.9 ± 0.1	0.16 ± 0.03	0.08 ± 0.01	0.06 ± 0.01	322 ± 1	
Cotton Stalk Biochar	250	71.17 ± 0.49	50.93	5.29	33.00	1.29	0.18	10.39	64.79	4.19	[66]
Cotton Stalk Biochar	350	42.75 ± 0.63	60.33	4.17	19.15	1.56	0.24	6.91	31.74	4.37	
Cotton Stalk Biochar	450	35.62 ± 0.53	64.52	3.27	12.65	1.51	0.29	5.07	19.61	4.57	
Cotton Stalk Biochar	550	33.21 ± 0.11	66.70	2.54	10.77	1.33	0.26	3.81	16.15	6.04	
Cotton Stalk Biochar	650	31.39 ± 0.29	67.77	1.89	9.07	1.24	0.30	2.79	13.38	4.43	

without regular microstructures. The surface of the derived biochar displays evident continuous pore channels. This not only preserves the original framework but also significantly increases the specific surface area of the biomass. This could potentially enhance adsorption capabilities and provide space for the attachment of microorganisms, which may be beneficial for studies in environmental microbiology. A significant correlation was seen between surface area and total pore volume [56]. Generally, a high surface area is considered beneficial for biochar when used for soil amendments. Previous studies have reported high surface areas and porosities in coconut shell biochar, suggesting its strong water retention properties and potential as a habitat for microbial communities [57]. However, the higher pyrolysis temperature leads to severe surface fragmentation in certain areas of the derived biochar, suggesting the potential for optimizing pyrolysis temperature conditions to achieve better outcomes.

As presented in Table 1, cottonseed hull biochar and cotton stalk biochar exhibit significant physicochemical property changes at different pyrolysis temperatures. With the increase in temperature, the yield of both types of biochar gradually decreases, a result that is corroborated by findings in other studies [60, 61]. Additionally, biochar surface roughness and pore structure characteristics were significantly influenced by the pyrolysis temperature. Simultaneously, the carbon content rises with temperature, reflecting the volatilization of non-carbon elements and an increase in the degree of carbonization during the pyrolysis process [62]. Furthermore, the decrease in H/C and O/C ratios suggests that the structure of biochar is evolving towards increased stability and aromatization [63]. The increase in surface area indicates a significant improvement in the porous structure of the biochar as the pyrolysis temperature increases, which may positively impact its application performance [64]. Overall, these changes reflect the significant influence of temperature on the characteristics of biochar, providing guidance for optimizing the production and application of biochar.

The role of cotton byproduct-derived biochar in soil reclamation

Research has indicated various significant roles of cotton byproducts-derived biochar in agricultural and environmental conservation. Scholars explored the impact of cotton stalk-derived biochar on plant growth and the microbial activity in soils contaminated with PVC microplastics [67]. Their findings demonstrated that biochar addition significantly increased the dry matter production of plants and effectively reduced the negative impacts of PVC microplastics on soil enzymes and microbial communities, aiding in maintaining soil microbial function stability [67].

Further, a new study revealed that cotton stalk-derived biochar, when used as a soil amendment, is instrumental in enhancing soil restoration. It primarily functions by elevating the levels of key nutrients like organic carbon, available phosphorus, and potassium in the soil. Despite the minimal impact of cotton stalk-derived biochar on soil water retention, its application has demonstrated overall positive effects on soil quality and cotton growth [68]. Investigations through field experiments assessed the impact of cotton stalk and the derived biochar on cotton yield and the transformation of nitrogen fertilizers into soil organic nitrogen components. Their studies revealed that biochar amendment was more effective for increasing soil total nitrogen, apparent nitrogen recovery rate, and cotton yield as compared to raw cotton stalk. Long-term biochar application notably enhanced the nitrogen utilization efficiency and cotton yield, facilitating the conversion of nitrogen fertilizer into organic nitrogen in the soil and improving its stability in drip-irrigated cotton fields [69].

Research focused on converting cotton waste from the textile industry to phosphorus-doped biochar for removing dyes from textile wastewater and recycling the used biochar as a soil amendment. Their findings indicated that compost made from cotton-derived biochar effectively aids soil reclamation and promotes plant growth. The recycled biochar displayed a carbon content of 83.6%. After 45 days, a compost product stable in pH, electrical conductivity, C/N ratio, and ammonium nitrogen content was harvested. The developed compost, when used as a soil conditioner, significantly enhanced the growth of tomato plants [70]. A study emphasized the potential of cotton-derived biochar as a soil amendment in dryland agriculture. Their research indicated that the effects of biochar on plant growth, root development, and nitrogen-fixing nodulation varied depending on factors such as plant species, soil type, moisture conditions, and application rate. Particularly in sandy soils, biochar moderately improved soil water retention [71].

Furthermore, the utility of cotton byproduct-derived biochar extends to soil remediation, especially in contexts contaminated with heavy metals. It has been found that biochar produced from waste cotton effectively remedies soils contaminated with heavy metals, offering a feasible method to mitigate heavy metal threats to crops [72]. In addition, findings suggest that biochar derived from cotton stalks considerably lowers the availability of Cd in contaminated alkaline soils, assisting in reducing the negative impacts of heavy metals on cotton crops [73]. Moreover, research indicates that biochar made from sewage sludge and cotton stalks effectively immobilizes

Pb, Cu, and Zn in sandy loam soils, lessening their availability to plants [74].

In conclusion, these studies collectively showcase the vast potential of cotton-derived biochar for enhancing agricultural productivity and environmental protection, highlighting its role as an efficient soil amendment and its contribution to the principles of circular economy and sustainable development.

Benefits and mechanisms of carbon sequestration by biochar

In the realm of sustainable agriculture and environmental conservation, extensive research has been conducted to explore the multifaceted benefits of biochar. This section summarizes key findings from several studies, highlighting the diverse applications and impacts of biochar on soil properties, including improvement in soil structure and fertility [75], enhancement of root development and yield in plants [76], and mitigation of climate change through carbon sequestration [77].

Some studies focused on the effects of pyrolysis temperature on the physicochemical properties of biochar and its subsequent application in soil. It was observed that biochar produced at different pyrolysis temperatures exhibit varied effects on soil improvement [78]. Notably, the study found that these variations in biochar properties significantly contribute to soil carbon sequestration, thereby enhancing the ability of soil to capture and store carbon effectively. This finding underscores the importance of optimizing pyrolysis conditions to maximize environmental benefits of biochar. Another significant piece of research examined the impact of biochar amendment on the physical and chemical properties of saline soils, as well as on rice growth. The use of cotton stalk-modified biochar resulted in enhancing both the physical and chemical properties of soil through improvements in Electrical Conductivity (EC), Exchangeable Sodium Percentage (ESP), Cation Exchange Capacity (CEC), Soil Organic Carbon (SOC), Bulk Density (BD), and soil porosity. Data showed significant increases in grain/straw yield with cotton stalk-modified biochar amendments, with maize showing increases of 34.15% and 29.82%, and wheat showing increases of 25.11% and 15.03%, respectively, compared to the control. Moreover, biochar not only promotes rice growth in these challenging conditions but also aids in carbon sequestration within the soil, making it a viable strategy for enhancing agricultural productivity while also contributing to environmental protection [41].

Further research [76] evaluated the effects of different biochars on seed germination and seedling growth of wheat. This study demonstrated that the application of biochar can markedly enhance the growth of wheat, from germination through to the seedling stage. Additionally, the study pointed out the positive role of biochar in soil carbon sequestration, suggesting that its use in wheat cultivation could be an effective approach for both improving crop yields and mitigating climate change impacts [76]. In a study focusing on cotton straw-derived materials, researchers investigated their impact on native soil carbon mineralization. The findings were significant, showing that these cotton straw-derived biochar could slow down the carbon mineralization process in the soil. This ability to hinder carbon mineralization is crucial for carbon sequestration, as it prevents the rapid release of carbon back into the atmosphere, thereby contributing to long-term carbon storage in soils [27].

Lastly, the prospects of cotton byproduct-derived biochar for sustainable agriculture and mitigating climate change were thoroughly explored in a comprehensive study. This research highlighted that the role of biochar extends far beyond just improving soil quality. It emphasized the significant contributions of biochar to carbon sequestration and its potential to reduce greenhouse gas emissions. This study valorized cotton biomass components in making biochars for sustainable agricultural practices and its potential as a key player in efforts to combat climate change [79].

According to existing research on evaluating the carbon sequestration potential of biochars, the method calculates the amount of carbon from the feedstock expected to remain in the soil long-term after conversion to biochar and its addition to the soil [80]. This calculation is achieved through an equation that incorporates several key parameters: the mass of the feedstock (M) in grams, the yield of biochar (C_h) as a percentage of the original mass, the carbon content of the produced biochar ($\mathrm{CC_h}$), the recalcitrance index (R_{50}) assessing the biochar's stability or resistance to decomposition, and the carbon content of the feedstock (CF). Slow pyrolysis at 600 °C was undertaken to determine how yields and characteristics of biochars differ when produced from different agricultural residues.

As shown in Table 2, the carbon content in the raw material of cotton stalk biochar is 46.0%, which increases to 83.2% in the biochar after pyrolysis, showing a carbon sequestration potential of 23.8%. This indicates that cotton stalk biochar has a stronger carbon sequestration potential compared to straw biochar. The carbon sequestration potential of rice husk biochar is 26.0%, and coconut shell biochar shows the best performance with a potential of 28.7%; suggesting that different types of biochars may have better carbon sequestration capabilities. Therefore, it is meaningful to explore cotton byproduct-derived biochar in future research.

Table 2 Comparative characteristics and carbon sequestration potentials of different biochar types [81]

Biochar type	Biochar yield (%)	Oil yield (%)	Gas yield (%)	C (%)-biochar	C (%)-feedstock	R_{50}	Carbon sequestration potential (%)
Cotton stalk	28.0	53.6	18.4	83.2	46.0	0.50	23.8
wheat straw	30.3	50.0	17.6	75.3	48.1	0.46	21.3
Coconut fibre	30.8	47.8	25.1	82.6	44.7	0.49	26.8
Rice husk	39.0	33.5	21.8	54.5	42.5	0.54	26.0
Coconut shell	28.2	43.7	28.1	93.9	52.6	0.59	28.7

In conclusion, these studies collectively illustrate the diverse applications and benefits of biochar in agriculture and environmental conservation. Ability of these biochars to improve soil quality, enhance plant growth, and contribute to carbon sequestration and greenhouse gas reduction highlights its potential as a multifunctional tool for sustainable agriculture and a viable solution for climate change mitigation.

Conclusion and future prospects

Cotton byproduct-derived biochar is a new research field in the recent decade. There is considerable potential to use this material for soil restoration and carbon sequestration. Previous reports concentrate on characterizing cotton byproducts-derived biochar and evaluating the effects of biochar amendments on soil health and plant growth. Worldwide, the production and use of cotton byproducts-derived biochar and its contribution to carbon sequestration are still at the fledging stage. Meanwhile, the environmental functions and benefits of cotton byproducts-derived biochar have not been fully understood. Therefore, further research and field trials are required to improve application techniques, identify potential drawbacks, and optimize its utilization in various agricultural and environmental settings. Ongoing research is imperative to comprehensively understanding its potential advantages, environmental implications, and optimal application methods.

Future research challenges and considerations encompass studies on the bioavailability of nutrients in cotton byproduct-derived biochar and its effects on plant growth. Additionally, there is a need for long-term investigations to validate the impact of biochar application on soil health, plant productivity, and carbon sequestration. Furthermore, assessing the environmental consequences of large-scale biochar production and application, including energy inputs and associated emissions, is crucial.

It is suggested to study the whole supply chain of cotton byproducts-derived biochar, its effects on soil, crops and carbon cycle, and the functioning mechanisms. It is critical to form a systematic and comprehensive cotton byproducts-derived biochar research system to guide the commercial production and field application of this specialty soil amendment. Furthermore, it is suggested to establish a physicochemical property parameter database of cotton byproducts-derived biochar to compare the effects and differences of other types of biochar on soil remediation and carbon sequestration, which may provide guidance for the study of detailed parameters of biochar and the formulation of relevant standards. Finally, future research may have highlights on strengthening the selection and combination of different raw materials, improving the target properties of cotton byproduct-derived biochar, forming a series of products, achieving the maximum utilization of cotton byproduct-derived biochar efficacy, helping soil ecological restoration, and promoting global carbon reduction and carbon fixation synergies.

Acknowledgements

ZH is an employee of United States Department of Agriculture (USDA). Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by USDA. USDA is an equal opportunity provider and employer.

Author contributions

Yingru Tao: writing—original draft; Weiying Feng: writing, reviewing and funding; Zhongqi He: writing, reviewing and editing; Beibei Wang: writing, reviewing; Fang Yang: writing, reviewing and funding; Aainaa Izyan Nafsun: writing, reviewing and editing; Yazhai Zhang: investigation.

Funding

This research was jointly supported in part by the Science and Technology Major Project of Ordos City (ZD20232301), National Natural Science Foundation of China (41907338) and the Key Science-Technology Project of Inner Mongolia under Grant (2022YFHH0044). This work was also supported in part by United States Department of Agriculture (USDA)—Agricultural Research Service internal research project 6054-41000-113-000D (ZH).

Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

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

Author details

[1]School of Materials Science and Engineering, Beihang University, Beijing 100191, China. [2]USDA-ARS, Southern Regional Research Center, New Orleans, LA 70124, USA. [3]School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China. [4]State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China. [5]Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang, Malaysia. [6]College of Chemistry and Chemical Engineering, Hebei Normal University for Nationalities, Chengde 067000, China.

Received: 6 February 2024 Accepted: 9 April 2024

References

1. Lehmann J (2007) A handful of carbon. Nature 447:143–144. https://doi.org/10.1038/447143a
2. McLaughlin H, Littlefield AA, Menefee M, Kinzer A, Hull T, Sovacool BK, Bazilian MD, Kim J, Griffiths S (2023) Carbon capture utilization and storage in review: sociotechnical implications for a carbon reliant world. Renew Sust Energ Rev 177:113215. https://doi.org/10.1016/j.rser.2023.113215
3. Guo M, Uchimiya SM, He Z (2015) Agricultural and environmental applications of biochar: advances and barriers. In: Guo M, He Z, Uchimiya SM (eds) SSSA Special Publications. SSSAJ, Madison, pp 495–504
4. Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627. https://doi.org/10.1126/science.1097396
5. Yang Y, Tilman D, Furey G, Lehman C (2019) Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nat Commun 10:718. https://doi.org/10.1038/s41467-019-08636-w
6. Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen Z-S, Cheng K, Das BS, Field DJ, Gimona A, Hedley CB, Hong SY, Mandal B, Marchant BP, Martin M, McConkey BG, Mulder VL, O'Rourke S, Richer-de-Forges AC, Odeh I, Padarian J, Paustian K, Pan G, Poggio L, Savin I, Stolbovoy V, Stockmann U, Sulaeman Y, Tsui C-C, Vågen T-G, Van Wesemael B, Winowiecki L (2017) Soil carbon 4 per mille. Geoderma 292:59–86. https://doi.org/10.1016/j.geoderma.2017.01.002
7. Razzaghi F, Obour PB, Arthur E (2020) Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma 361:114055. https://doi.org/10.1016/j.geoderma.2019.114055
8. Lehmann J, Cowie A, Masiello CA, Kammann C, Woolf D, Amonette JE, Cayuela ML, Camps-Arbestain M, Whitman T (2021) Biochar in climate change mitigation. Nat Geosci 14:883–892. https://doi.org/10.1038/s41561-021-00852-8
9. Gong H, Zhao L, Rui X, Hu J, Zhu N (2022) A review of pristine and modified biochar immobilizing typical heavy metals in soil: applications and challenges. J Hazard Mater 432:128668. https://doi.org/10.1016/j.jhazmat.2022.128668
10. Wu F, Li F, Zhao X, Bolan NS, Fu P, Lam SS, Mašek O, Ong HC, Pan B, Qiu X, Rinklebe J, Tsang DCW, Van Zwieten L, Vithanage M, Wang S, Xing B, Zhang G, Wang H (2022) Meet the challenges in the "Carbon Age." Carbon Res 1:1. https://doi.org/10.1007/s44246-022-00001-9
11. Feng W, Wang T, Zhu Y, Sun F, Giesy JP, Wu F (2023) Chemical composition, sources, and ecological effect of organic phosphorus in water ecosystems: a review. Carbon Res 2:12. https://doi.org/10.1007/s44246-023-00038-4
12. Feng W, Gao J, Cen R, Yang F, He Z, Wu J, Miao Q, Liao H (2020) Effects of polyacrylamide-based super absorbent polymer and corn straw biochar on the arid and semi-arid salinized soil. Agriculture 10:519. https://doi.org/10.3390/agriculture10110519
13. Kwon G, Bhatnagar A, Wang H, Kwon EE, Song H (2020) A review of recent advancements in utilization of biomass and industrial wastes into engineered biochar. J Hazard Mater 400:123242. https://doi.org/10.1016/j.jhazmat.2020.123242
14. Osman AI, Fawzy S, Farghali M, El-Azazy M, Elgarahy AM, Fahim RA, Maksoud MIAA, Ajlan AA, Yousry M, Saleem Y, Rooney DW (2022) Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. Environ Chem Lett 20:2385–2485. https://doi.org/10.1007/s10311-022-01424-x
15. Feng W, Yang F, Cen R, Liu J, Qu Z, Miao Q, Chen H (2021) Effects of straw biochar application on soil temperature, available nitrogen and growth of corn. J Environ Manage 277:111331. https://doi.org/10.1016/j.jenvman.2020.111331
16. Pang S, Zhou C, Sun Y, Zhang K, Ye W, Zhao X, Cai L, Hui B (2023) Natural wood-derived charcoal embedded with bimetallic iron/cobalt sites to promote ciprofloxacin degradation. J Clean Prod 414:137569. https://doi.org/10.1016/j.jclepro.2023.137569
17. Qiu B, Tao X, Wang H, Li W, Ding X, Chu H (2021) Biochar as a low-cost adsorbent for aqueous heavy metal removal: a review. J Anal Appl Pyrols 155:105081. https://doi.org/10.1016/j.jaap.2021.105081
18. Wu H, Lai C, Zeng G, Liang J, Chen J, Xu J, Dai J, Li X, Liu J, Chen M, Lu L, Hu L, Wan J (2017) The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review. Crit Rev Biotechnol 37:754–764. https://doi.org/10.1080/07388551.2016.1232696
19. Oladele SO, Adeyemo AJ, Awodun MA (2019) Influence of rice husk biochar and inorganic fertilizer on soil nutrients availability and rain-fed rice yield in two contrasting soils. Geoderma 336:1–11. https://doi.org/10.1016/j.geoderma.2018.08.025
20. Liang J, Tang S, Gong J, Zeng G, Tang W, Song B, Zhang P, Yang Z, Luo Y (2020) Responses of enzymatic activity and microbial communities to biochar/compost amendment in sulfamethoxazole polluted wetland soil. J Hazard Mater 385:121533. https://doi.org/10.1016/j.jhazmat.2019.121533
21. Wu P, Ata-Ul-Karim ST, Singh BP, Wang H, Wu T, Liu C, Fang G, Zhou D, Wang Y, Chen W (2019) A scientometric review of biochar research in the past 20 years (1998–2018). Biochar 1:23–43. https://doi.org/10.1007/s42773-019-00002-9
22. He Z, Nam S, Liu S, Zhao Q (2023) Characterization of the nonpolar and polar extractable components of glanded cottonseed for its valorization. Molecules 28:4181. https://doi.org/10.3390/molecules28104181
23. Cheng HN, He Z, Ford C, Wyckoff W, Wu Q (2020) A review of cottonseed protein chemistry and non-food applications. Sustain Chem 1:256–274. https://doi.org/10.3390/suschem1030017
24. He Z, Zhang H, Tewolde H, Shankle M (2017) Chemical characterization of cotton plant parts for multiple uses. Agric Environ Lett 2:110044. https://doi.org/10.2134/ael2016.11.0044
25. Nam S, Easson M, Jordan JH, He Z, Zhang H, Santiago Cintrón M, Chang S (2023) Unveiling the hidden value of cotton gin waste: natural synthesis and hosting of silver nanoparticles. ACS Omega 8:31281–31292. https://doi.org/10.1021/acsomega.3c03653
26. Wanjura JD, Barnes EM, Kelley MS, Holt GA, Pelletier MG (2014) Quantification and characterization of cotton crop biomass residue. Ind Crops Prod 56:94–104. https://doi.org/10.1016/j.indcrop.2014.02.019
27. Allesina G, Pedrazzi S, Allegretti F, Morselli N, Puglia M, Santunione G, Tartarini P (2018) Gasification of cotton crop residues for combined power and biochar production in Mozambique. Appl Therm Eng 139:387–394. https://doi.org/10.1016/j.applthermaleng.2018.04.115
28. Schaffer S, Pröll T, Al Afif R, Pfeifer C (2019) A mass- and energy balance-based process modelling study for the pyrolysis of cotton stalks with char utilization for sustainable soil enhancement and carbon storage. Biomass Bioenerg 120:281–290. https://doi.org/10.1016/j.biombioe.2018.11.019
29. Zhu S, Liu J, Tang G, Sun T, Jia H, Zhao H, Zhang Y, Lin L, Xu W (2023) Evaluating the application potential of acid-modified cotton straw biochars in alkaline soils based on entropy weight TOPSIS. Agronomy 13:2807. https://doi.org/10.3390/agronomy13112807
30. Fan X, Wang X, Cai Y, Xie H, Han S, Hao C (2022) Functionalized cotton charcoal/chitosan biomass-based hydrogel for capturing Pb2+, Cu2+ and MB. J Hazard Mater 423:127191. https://doi.org/10.1016/j.jhazmat.2021.127191
31. Çay A, Yanık J, Akduman Ç, Duman G, Ertaş H (2020) Application of textile waste derived biochars onto cotton fabric for improved

performance and functional properties. J Cleaner Prod 251:119664. https://doi.org/10.1016/j.jclepro.2019.119664
32. Feng W, Deng Y, Cao Y, Liu J, Han Y, Liu J, Miao Q, Yang F, Zhu Y, Giesy JP (2023) Biotechnology remediation and environmental behavior of microplastics in soils: a review. Rev Environ Contam (formerly: residue reviews) 261:13. https://doi.org/10.1007/s44169-023-00038-w
33. Olawumi TO, Chan DWM (2018) A scientometric review of global research on sustainability and sustainable development. J Clean Prod 183:231–250. https://doi.org/10.1016/j.jclepro.2018.02.162
34. Yang X-B, Ying G-G, Peng P-A, Wang L, Zhao J-L, Zhang L-J, Yuan P, He H-P (2010) Influence of biochars on plant uptake and dissipation of two pesticides in an agricultural soil. J Agric Food Chem 58:7915–7921. https://doi.org/10.1021/jf1011352
35. Pandirwar AP, Khadatkar A, Mehta CR, Majumdar G, Idapuganti R, Mageshwaran V, Shirale AO (2023) Technological advancement in harvesting of cotton stalks to establish sustainable raw material supply chain for industrial applications: a review. Bioenerg Res 16:741–760. https://doi.org/10.1007/s12155-022-10520-3
36. Xing G, Zhu Z (2000) An assessment of N loss from agricultural fields to the environment in China. Nutr Cycling Agroecosyst 57:67–73. https://doi.org/10.1023/A:1009717603427
37. The Price Department of the National Development and Reform Commission of China, 2004–2018. National Agricultural Product Cost Income Data Compilation. China Statistics Press, Beijing.
38. Huang W, Wu F, Zhang Z, Meng Y, Wang J, Li Q, Han Y, Feng L, Li X, Wang G, Lei Y, Fan Z, Yang B, Xiong S, Xin M, Li Y, Wang Z (2023) The nitrogen footprint and reactive nitrogen reduction potential of cotton production in China. J Cleaner Prod 402:136808. https://doi.org/10.1016/j.jclepro.2023.136808
39. Fahmy TYA, Fahmy Y, Mobarak F, El-Sakhawy M, Abou-Zeid RE (2020) Biomass pyrolysis: past, present, and future. Environ Dev Sustain 22:17–32. https://doi.org/10.1007/s10668-018-0200-5
40. Akpomie KG, Conradie J (2020) Advances in application of cotton-based adsorbents for heavy metals trapping, surface modifications and future perspectives. Ecotoxicol Environ Safe 201:110825. https://doi.org/10.1016/j.ecoenv.2020.110825
41. El-Sharkawy M, El-Naggar AH, Al-Huqail AA, Ghoneim AM (2022) Acid-modified biochar impacts on soil properties and biochemical characteristics of crops grown in saline-sodic soils. Sustainability 14:8190. https://doi.org/10.3390/su14138190
42. Chen Y, Lin M, Zhuang D (2022) Wastewater treatment and emerging contaminants: Bibliometric analysis. Chemosphere 297:133932. https://doi.org/10.1016/j.chemosphere.2022.133932
43. He Z, Uchimiya SM, Guo M (2015) Production and characterization of biochar from agricultural by-products: overview and use of cotton biomass residues. In: Guo M, He Z, Uchimiya SM (eds) SSSA special publications. American Society of Agronomy and Soil Science Society of America, Madison, pp 63–86
44. Mao A, He Z, Wan H, Li Q (2017) Bio-based wood adhesives: preparation, characterization, and testing. Biobased wood adhesives: preparation, characterization, and testing. CRC Press, Boca Raton, pp 260–279
45. Liu Y, He Z, Uchimiya M (2015) Comparison of biochar formation from various agricultural by-products using FTIR spectroscopy. MAS 9:p246. https://doi.org/10.5539/mas.v9n4p246
46. Uchimiya M, Ohno T, He Z (2013) Pyrolysis temperature-dependent release of dissolved organic carbon from plant, manure, and biorefinery wastes. J Anal Appl Pyrolysis 104:84–94. https://doi.org/10.1016/j.jaap.2013.09.003
47. Chen Y, Yang H, Wang X, Zhang S, Chen H (2012) Biomass-based pyrolytic polygeneration system on cotton stalk pyrolysis: influence of temperature. Bioresour Technol 107:411–418. https://doi.org/10.1016/j.biortech.2011.10.074
48. Tariq MA, Nadeem M, Iqbal MM, Imran M, Siddique MH, Iqbal Z, Amjad M, Rizwan M, Ali S (2020) Effective sequestration of Cr (VI) from wastewater using nanocomposite of ZnO with cotton stalks biochar: modeling, kinetics, and reusability. Environ Sci Pollut Res 27:33821–33834. https://doi.org/10.1007/s11356-020-09481-x
49. Sun J, Lian F, Liu Z, Zhu L, Song Z (2014) Biochars derived from various crop straws: characterization and Cd(II) removal potential. Ecotox Environ Safe 106:226–231. https://doi.org/10.1016/j.ecoenv.2014.04.042
50. Xu Z, Zhou Y, Sun Z, Zhang D, Huang Y, Gu S, Chen W (2020) Understanding reactions and pore-forming mechanisms between waste cotton woven and FeCl3 during the synthesis of magnetic activated carbon. Chemosphere 241:125120. https://doi.org/10.1016/j.chemosphere.2019.125120
51. Iqbal MM, Imran M, Hussain T, Naeem MA, Al-Kahtani AA, Shah GM, Ahmad S, Farooq A, Rizwan M, Majeed A, Khan AR, Ali S (2021) Effective sequestration of Congo red dye with ZnO/cotton stalks biochar nanocomposite: MODELING, reusability and stability. J Saudi Chem Soc 25:101176. https://doi.org/10.1016/j.jscs.2020.101176
52. Yaashikaa PR, Kumar PS, Varjani S, Saravanan A (2020) A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. Biotechnol Rep 28:e00570. https://doi.org/10.1016/j.btre.2020.e00570
53. Cen R, Feng W, Yang F, Wu W, Liao H, Qu Z (2021) Effect mechanism of biochar application on soil structure and organic matter in semi-arid areas. J Environ Manage 286:112198. https://doi.org/10.1016/j.jenvman.2021.112198
54. Feng W, Wang T, Yang F, Cen R, Liao H, Qu Z (2023) Effects of biochar on soil evaporation and moisture content and the associated mechanisms. Environ Sci Eur 35:66. https://doi.org/10.1186/s12302-023-00776-7
55. He Z, Guo M, Sleighter RL, Zhang H, Chanel F, Hatcher PG (2018) Characterization of defatted cottonseed meal-derived pyrolysis bio-oil by ultrahigh resolution electrospray ionization Fourier transform ion cyclotron resonance mass spectrometry. J Anal Appl Pyrolysis 136:96–106. https://doi.org/10.1016/j.jaap.2018.10.018
56. Muzyka R, Misztal E, Hrabak J, Banks SW, Sajdak M (2023) Various biomass pyrolysis conditions influence the porosity and pore size distribution of biochar. Energy 263:126128. https://doi.org/10.1016/j.energy.2022.126128
57. Atkinson CJ, Fitzgerald JD, Hipps NA (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337:1–18. https://doi.org/10.1007/s11104-010-0464-5
58. He Z, Guo M, Fortier C, Cao X, Schmidt-Rohr K (2021) Fourier transform infrared and solid state 13C nuclear magnetic resonance spectroscopic characterization of defatted cottonseed meal-based biochars. MAS 15:108. https://doi.org/10.5539/mas.v15n1p108
59. Guo M, He Z, Tian J (2024) Fractionation and lability of phosphorus species in cottonseed meal-derived biochars as influenced by pyrolysis temperature. Molecules 29:303. https://doi.org/10.3390/molecules29020303
60. He X, Liu Z, Niu W, Yang L, Zhou T, Qin D, Niu Z, Yuan Q (2018) Effects of pyrolysis temperature on the physicochemical properties of gas and biochar obtained from pyrolysis of crop residues. Energy 143:746–756. https://doi.org/10.1016/j.energy.2017.11.062
61. Zhang X, Zhang P, Yuan X, Li Y, Han L (2020) Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. Bioresour Technol 296:122318. https://doi.org/10.1016/j.biortech.2019.122318
62. Tomczyk A, Sokołowska Z, Boguta P (2020) Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev Environ Sci Biotechnol 19:191–215. https://doi.org/10.1007/s11157-020-09523-3
63. Das SK, Ghosh GK, Avasthe RK, Sinha K (2021) Compositional heterogeneity of different biochar: Effect of pyrolysis temperature and feedstocks. J Environ Manage 278:111501. https://doi.org/10.1016/j.jenvman.2020.111501
64. Leng L, Xiong Q, Yang L, Li H, Zhou Y, Zhang W, Jiang S, Li H, Huang H (2021) An overview on engineering the surface area and porosity of biochar. Sci Total Environ 763:144204. https://doi.org/10.1016/j.scitotenv.2020.144204
65. Uchimiya M, Wartelle LH, Klasson KT, Fortier CA, Lima IM (2011) Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil. J Agric Food Chem 59:2501–2510. https://doi.org/10.1021/jf104206c
66. Gao L, Li Z, Yi W, Li Y, Zhang P, Zhang A, Wang L (2021) Impacts of pyrolysis temperature on lead adsorption by cotton stalk-derived biochar and related mechanisms. J Environ Chem Eng 9:105602. https://doi.org/10.1016/j.jece.2021.105602
67. Khalid A, Shah T, Asad M, Ali A, Samee E, Adnan F, Bhatti M, Marhan S, Kammann C, Haider G (2023) Biochar alleviated the toxic effects of PVC

microplastic in a soil-plant system by upregulating soil enzyme activities and microbial abundance. Environ Pollut. https://doi.org/10.1016/j.envpol.2023.121810
68. Tang M, Liu R, Luo Z, Zhang C, Kong J, Feng S (2023) Straw returning measures enhance soil moisture and nutrients and promote cotton growth. Agron Basel. https://doi.org/10.3390/agronomy13071850
69. Ma L, Huo Q, Tian Q, Xu Y, Hao H, Min W, Hou Z (2023) Continuous application of biochar increases 15N fertilizer translocation into soil organic nitrogen and crop uptake in drip-irrigated cotton field. J Soils Sediments 23:1204–1216. https://doi.org/10.1007/s11368-022-03416-4
70. Kar S, Santra B, Kumar S, Ghosh S, Majumdar S (2022) Sustainable conversion of textile industry cotton waste into P-dopped biochar for removal of dyes from textile effluent and valorisation of spent biochar into soil conditioner towards circular economy. Environ Pollut. https://doi.org/10.1016/j.envpol.2022.120056
71. Haddad S, Mowrer J, Thapa B (2022) Biochar and compost from cotton residues inconsistently affect water use efficiency, nodulation, and growth of legumes under arid conditions. J Environ Manage. https://doi.org/10.1016/j.jenvman.2022.114558
72. Li Y, Shao M, Huang M, Sang W, Zheng S, Jiang N, Gao Y (2022) Enhanced remediation of heavy metals contaminated soils with EK-PRB using β-CD/hydrothermal biochar by waste cotton as reactive barrier. Chemosphere 286:131470. https://doi.org/10.1016/j.chemosphere.2021.131470
73. Zhu Y, An M, Mamut R, Wang H (2023) Comparative analysis of metabolic mechanisms in the remediation of Cd-polluted alkaline soil in cotton field by biochar and biofertilizer. Chemosphere 340:139961. https://doi.org/10.1016/j.chemosphere.2023.139961
74. Wang Z, Shen R, Ji S, Xie L, Zhang H (2021) Effects of biochar derived from sewage sludge and sewage sludge/cotton stalks on the immobilization and phytoavailability of Pb, Cu, and Zn in sandy loam soil. J Hazard Mater 419:126468. https://doi.org/10.1016/j.jhazmat.2021.126468
75. Wu X, Wang D, Riaz M, Zhang L, Jiang C (2019) Investigating the effect of biochar on the potential of increasing cotton yield, potassium efficiency and soil environment. Ecotox Environ Safe 182:109451. https://doi.org/10.1016/j.ecoenv.2019.109451
76. Khan Z, Rahman M, Haider G, Amir R, Ikram R, Ahmad S, Schofield H, Riaz B, Iqbal R, Fahad S, Datta R, Baazeem A, Sabagh A, Danish S (2021) Chemical and biological enhancement effects of biochar on wheat growth and yield under arid field conditions. Sustainability. https://doi.org/10.3390/su13115890
77. Primaz CT, Ribes-Greus A, Jacques RA (2021) Valorization of cotton residues for production of bio-oil and engineered biochar. Energy 235:121363. https://doi.org/10.1016/j.energy.2021.121363
78. Chen D, Zheng Z, Fu K, Zeng Z, Wang J, Lu M (2015) Torrefaction of biomass stalk and its effect on the yield and quality of pyrolysis products. Fuel 159:27–32. https://doi.org/10.1016/j.fuel.2015.06.078
79. He Z, Olk D, Tewolde H, Zhang H, Shankle M (2020) Carbohydrate and amino acid profiles of cotton plant biomass products. Agric Basel. https://doi.org/10.3390/agriculture10010002
80. Zhao L, Cao X, Mašek O, Zimmerman A (2013) Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. J Hazard Mater 256–257:1–9. https://doi.org/10.1016/j.jhazmat.2013.04.015
81. Windeatt JH, Ross AB, Williams PT, Forster PM, Nahil MA, Singh S (2014) Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. J Hazard Mater 146:189–197. https://doi.org/10.1016/j.jenvman.2014.08.003

Publisher's Note