

Carbonization of Agricultural Waste for Water Pollution Control in Agro-Pastoral Zones: Research Progress, Challenges, and Future Prospects

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Abstract: The intertwined development of agriculture and animal husbandry has exacerbated water pollution risks in agro-pastoral zones. Agricultural waste, if improperly managed, leads to the migration of nitrogen, phosphorus, heavy metals, and pathogens into water bodies, causing eutrophication and deterioration of water quality. Carbonization of agricultural waste, particularly through the application of biochar, offers a promising strategy to mitigate these environmental challenges while enhancing soil quality and promoting sustainable agriculture. This review systematically analyzes the mechanisms, environmental benefits, and influencing factors of carbonization technology in the unique climatic and hydrological conditions of agro-pastoral regions. It identifies key challenges including climatic variability, lack of standardized biochar production protocols, limited long-term monitoring, and economic constraints. Future research directions are proposed, emphasizing interdisciplinary approaches, technological integration, dynamic adaptation to climate change, and supportive policy frameworks. This study provides a scientific basis for optimizing the application of carbonization technology to improve ecological resilience, water security, and agricultural sustainability in vulnerable agro-pastoral ecosystems.

Keywords: Agricultural waste carbonization, Agro-pastoral zone, Biochar, Water pollution control, Climate adaptation, Sustainable agriculture, Soil quality improvement

1. Introduction

Today, the global ecosystem is becoming more fragile. As a transition zone between agriculture and pastoralism, the impact of agricultural production activities on the pollution of water becomes more and more serious. With the development of agriculture and animal husbandry, a large amount of agricultural waste such as crop residues and animal manure is generated. Livestock wastewater contains heavy metals and pathogens. Chronic untreated manure can lead to the accumulation of groundwater and soil toxicity and reduce soil fertility and crop productivity [1]. If agricultural waste is not properly treated, it can lead to the flow of nitrogen, phosphorus, heavy metals and pathogens into water bodies. This will lead to eutrophication, deterioration of water quality, threatening the ecology and the safety of water for residents, so effective treatment and utilization is urgent.

Carbonization to field technology is getting a lot of attention, especially biomass charcoal technology. The technology combines pyrolytic carbonization of agricultural wastes under anoxic or

oxygen-limited conditions. The resulting biomass charcoal is applied to the soil. Thanks to its rich pore structure and large specific surface area, biomass charcoal can adsorb pollutants in water bodies and slow down their migration to water bodies. Therefore, there is a huge potential for preventing and controlling pollution in the water environment [2,3]. It also enables waste to be resourced, improves soil quality and promotes sustainable agricultural development. It also enables waste to be resourced, improves soil quality and promotes sustainable agricultural development.

Carbonization of agricultural waste back to the field technology faces dilemmas in practical applications. There are significant differences in effectiveness due to the complexity of the conditions. Waste materials are diverse, with straw, rice husk, animal manure and other components having different characteristics. This affects the nature of carbonation products. Research has found that the heavy metal removal potential of biochar from different feedstock sources in multi-heavy metal solutions varies widely [4]. Different modes of production also make a difference in product structure and function. Environmental factors such as soil texture, acidity and alkalinity and the degree of water pollution are determining factors for the effectiveness of pollution prevention and control in their water environments. Most of the previous studies on the carbonization of agricultural waste to land have focused on general agricultural areas or broader ecosystems. There is a serious lack of in-depth exploration of agro-pastoral zones, which are special areas with both agricultural and pastoral characteristics, extremely sensitive ecosystems and strong transitions. This has led to many uncertainties in the promotion and application of this technology in the agro-pastoral zone.

The present study focused on the agro-pastoral zone, considering the unique ecological characteristics of the region, such as climatic variability, complex soil texture, and mixed agricultural and pastoral production patterns. To be able to more accurately assess the effectiveness and mechanism of action of carbonation of agricultural wastes back to the field in the prevention and control of water environmental pollution in the region.

2. Carbonization of agricultural waste to land

Traditional agricultural waste disposal mostly uses landfills and open burning. Landfills take up a lot of land and generate leachate containing heavy metals and organic pollutants. When seepage control is poor, it can seep down and contaminate soil water and groundwater, threatening water safety and human health. Open burning produces acidic gases. These acid gases can form acid rain that flows into surface water bodies, altering pH levels, dissolving soil heavy metals and polluting surface water.

The technology of carbonization of agricultural waste back to the field has become the key to breaking such a situation. Under an anoxic or low oxygen environment, it uses pyrolysis technology to convert straw, rice husk, animal manure and other waste into carbon and mineral-rich biochar with special physicochemical structure. Not only can it realize the resourceful use of agricultural waste, but it can also improve soil structure, but also improve soil fertility, promote crop growth, and have a positive effect on the improvement of water environment pollution [5].

With the increased global focus on sustainable agriculture, technology has become a focal point for scientific research and agricultural practices. Figure 1 shows the number of studies published on the carbonization of agricultural waste to land from 2013 to 2024 based on data retrieved from ScienceDirect, highlighting the heat and importance of this technology at the academic research level. Figure 2 shows the main keywords used in the application article and the search terms used on the scientific network. The terms 'energy', 'adsorption', 'activation', 'porous structure', 'super capacitor', etc. are terms with a high degree of control. The terms 'structure', 'super capacitor', etc. are terms with a high degree of control. This may indicate that research has focused mainly on energy storage, adsorption properties, activation processes and porous structures. This shows the potential of agricultural waste for energy and environmental applications.

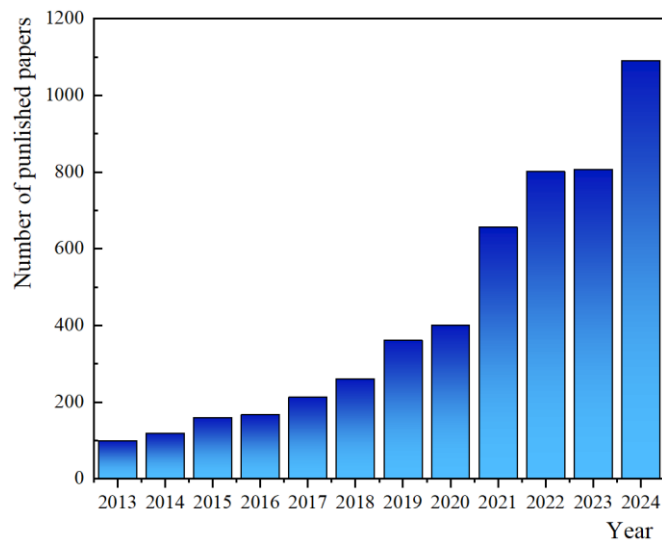


Figure 1: The number of published reports on carbonization of agricultural waste to land, with data sourced from ScienceDirect

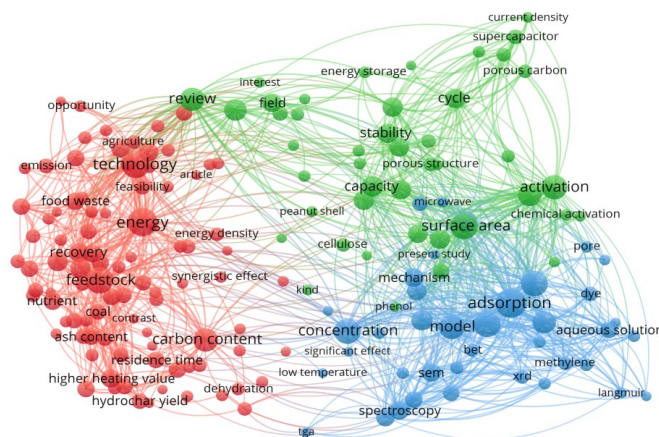


Figure 2: Hop map of keywords for articles on agricultural waste carbonization using VOSviewer software

From the point of view of environmental benefits, the advantages of the technology of carbonization of agricultural wastes to fields are outstanding. It reduces waste pollution at source, and biochar sequestration slows greenhouse gas emissions [6]. In agricultural production, the porous structure of biochar applied to soil can improve soil physical properties. It enhances aeration, water and fertilizer retention capacity, provides a habitat for microorganisms, improves soil biological activity, helps increase crop yields and improve quality, and ensures food security. Technology fits the concept of sustainable agriculture and is integrated into the agricultural production system. It can improve soil health, optimize material and energy cycles, reduce costs and increase efficiency, and promote the transformation and upgrading of the agricultural industry.

3. Differences and impacts of carbonation returns in agro-pastoral zones

The agro-pastoral zone is a transition zone between agriculture and pastoralism, with unique climatic and hydrological conditions. The complexity and variability of its climate, which is mostly arid, semi-arid or semi-humid, with low and unevenly distributed precipitation, significantly affects

carbon-to-field technology. The carbonization process requires stable temperatures (350°C to 700°C). However, the region has a large diurnal temperature difference, with cold winters and hot summers. Temperature fluctuations may affect equipment operation and reduce carbonization efficiency. Although high temperatures enhance efficiency, excessive temperatures may disrupt the pore structure of biochar and weaken its adsorption capacity [7]. In addition, low and uneven precipitation resulted in low soil moisture. Biochar's ability to absorb and retain water is critical to soil moisture retention. In drought conditions, biochar improves soil water holding capacity, reduces evaporation and improves soil structure. However, the adsorption capacity of biochar may be saturated when there is more precipitation, affecting its adsorption effect. Therefore, carbonation techniques need to be optimized for temperature fluctuations and uneven precipitation to adapt to the climatic conditions of the agro-pastoral zone.

The agro-pastoral zone has complex hydrological conditions, with uneven distribution of surface water and groundwater and significant differences in water quality. This has important implications for the application of carbon-to-field technology. During the rainy season, concentrated surface runoff may carry pollutants from agricultural waste into water bodies, causing pollution of the water environment. Although biochar can effectively adsorb nutrients such as nitrogen and phosphorus from soil and reduce the risk of migration with runoff, the adsorption capacity of biochar may be insufficient in areas of high runoff, and some pollutants will still enter the water body [8]. In addition, groundwater resources are scarce and vulnerable to pollution. Although biochar can absorb heavy metals and organic pollutants and reduce the risk of their migration to groundwater, the adsorption capacity is limited in areas of high-water table, and some of the pollutants may leach into groundwater. Therefore, carbonation to field technology needs to be combined with hydrological characteristics to optimize the amount and manner of biochar application to minimize the risk of pollution of the water environment.

Table 1: Research on factors affecting carbonization and return-to-field technology

Factors	Characteristics	Influence	Optimization strategies	Reference
Climatic conditions	Uneven and insufficient precipitation	Biochar's water-holding and adsorption capacity decline	Improve soil water retention capacity Shade	[9]
	Strong light intensity	Alter biochar properties and fertility	combination with fertilization	[10]
	Large diurnal temperature difference	Affecting the carbonization equipment in reducing carbonization efficiency	Improve the temperature control system	[11]
	Significant differences in water quality	Unstable water sources affect the application effect of biochar.	Optimize the application method of biochar	[8]
Hydrological conditions	The rainy season has strong runoff, carrying pollutants.	Exceeding the adsorption capacity of biochar, pollution runoff.	Select the appropriate application location	[9]
	The amount of groundwater resources shows significant changes.	Adsorption capacity is limited, pollutants penetrate groundwater.	Control the application depth	[12]

4. The effect of climate on the prevention and control of water pollution in carbon-based field returns

The impact of carbonation return on water pollution prevention and control in the agro-pastoral zone is governed by climatic factors, which are classified as internally and externally induced. Internal factors mainly include temperature, precipitation and wind speed. Temperature directly affects microbial activity, and thus the rate of decomposition and nutrient release from carbonation to land. Higher temperatures accelerate decomposition and lead to nutrient loss. Too low a temperature inhibits decomposition and reduces the return effect. Precipitation determines soil moisture status and affects microbial activity and nutrient transport. Too much precipitation may lead to nutrient leaching, too little limits microbial activity [13]. Precipitation intensity is also critical. Heavy rainfall tends to trigger surface runoff, which results in the loss of nutrients and carbonated materials and increases the risk of water pollution. In addition, wind speed also affects the effect of carbonation on field return. Strong winds accelerate soil moisture evaporation. It leads to impaired decomposition of carbonated material and may also trigger wind erosion, resulting in nutrient loss.

External factors include mainly extreme weather events and climate change. Extreme climatic events such as droughts and floods can have a significant impact on carbon return. Drought not only inhibits microbial activity and slows the decomposition of carbonized material, but it also reduces the effectiveness of field reclamation and increases the risk of wind erosion [14]. Flooding accelerates carbonate decomposition and nutrient release, increasing the risk of nutrient loss and water pollution. Climate change is also an important factor affecting the effectiveness of carbonation in returning land. Warmer temperatures may accelerate the decomposition of carbonated material and increase the risk of nutrient release and loss. Changes to rainfall patterns may lead to uneven distribution of precipitation, exacerbating droughts or floods and affecting the effectiveness of carbonation for land reuse. In addition, an increase in the frequency of extreme weather events would increase the potential risk of water pollution from carbonation of field returns.

Table 2: Research on the impact of climate

Factors	Influence	Research Methodology	Optimization Strategy	Reference
Temperature	Alter the composition of microbial communities	Barcoded pyrophosphate sequencing method	Choose the appropriate time for returning farmland to its original state.	[15]
Precipitation	Alter the quantity and quality of soil organic matter	Simulated precipitation, long-term monitoring	Timely watering	[16]
Wind speed	Water evaporation, wind erosion intensifies	Establish a model	Windbreak cover, straw mulching	[17]
Drought	Inhibit decomposition	Data collection, comprehensive analysis	Reasonable irrigation	[18]
Extreme climate	Organic carbon loss	Digital Soil Mapping Technology	Formulate targeted regional policies	[19]

5. Shortcomings of existing research

Carbonization of agricultural wastes in agricultural and pastoral zones is gaining attention. However, there are many shortcomings in practical applications. Firstly, the long-term effects of climate variability and weather extremes on the effectiveness of carbonation to land have also not been deeply researched. Climate change changes precipitation, temperature and other conditions that affect biomass carbon stability and effectiveness. However, most of the existing studies are based on static climate and lack adaptation analyses in a dynamic context. Making the future of technology's application doubtful. For example, Kammann et al. [20] noted that extreme weather events may significantly affect the stability of biomass charcoal and its effectiveness as a soil amendment.

Secondly, there is a lack of uniform standards for biomass charcoal preparation, application and monitoring. The quality and effect of biomass charcoal is affected by raw materials, charging temperature and other factors. However, there are currently no uniform technical specifications. This makes it difficult to compare data from different studies and affects the scientific validity of the results. There is also a lack of information on application rates, application methods, and monitoring and evaluation of the effects on soil micro-organisms and plant growth. This limits optimization of technology. At the same time, research focuses on short-term effects that lack long-term orientation monitoring and evaluation. The long-term stability and environmental risks of carbon-to-field technology have not been adequately researched, such as the rate of degradation of biomass charcoal, the impact on soil organic carbon pools and groundwater quality. Long-term monitoring is missing, preventing a full evaluation of technical sustainability and environmental safety.

There are also challenges with the economics of technology and its diffusion. The applicability of carbonization technologies varies greatly from region to region. Carbonizer costs, operational requirements and energy availability affect economic viability and diffusion. The balance between policy support and economic returns to farmers needs to be explored. Initial investment in technology is high, and short-term benefits to farmers are not obvious. Policy incentives and subsidies are needed to reduce the burden.

In conclusion, the carbonization of agricultural waste in the agro-pastoral zone is deficient in terms of climate adaptation, technical standards, long-term monitoring and economic viability. In the future, adaptation under climate change should be explored more intensively, standards should be developed, long-term monitoring should be carried out, and policymakers should focus on economics. To achieve a double win in terms of environmental benefits and farmers' profitability and promote the widespread use of technology.

6. Future research directions and applications

Although agricultural waste carbonization technology is currently an important method of ecological management and resource recycling in the agricultural and pastoral intertwined zone, it still needs to be deeply researched in the direction of multidisciplinary intersection, technology integration and policy collaboration.

At the multidisciplinary level, the impacts of carbon-return on soil carbon pool dynamics, microbial communities and greenhouse gas emissions need to be analyzed in depth by combining molecular biology and geochemistry. Biochar changes soil pore structure and pH. Biochar changes soil pore structure and pH. Regulation of the proportion of bacterial versus fungal denitrification pathways contributing to N₂O emissions. The future must be targeted to different climatic zones and soil types. Exploring the mechanisms of biochar regulation of functional genes and enzyme activities of the nitrogen cycle. Tracking its long-term effects on soil organic matter with the help of isotope labelling techniques to reveal the potential for carbon sequestration [21].

In technology integration, biomass carbon preparation parameters need to be integrated and optimized with regional resource characteristics. Biochar generated from different feedstocks and pyrolysis temperatures has different effects. Returning methods are also divided into shallow rotary ploughing and deep mixed returning, with application scenarios varying. With the help of big data and intelligent decision-making system, build a regional carbonization and field return management platform, integrate various data and models, and dynamic recommendation of application rate and field return mode.

Policy synergies shouldn't be overlooked. There is a need to develop technical standards and industry-wide support policies for carbonization. Initial financial aid to stimulate farmers, with a shift to market-based operations at a later period. Promoting science-enterprise collaboration demonstration projects. Expand pilots through policy guidance to improve agricultural waste collection, storage and transport systems and reduce costs.

The establishment of integrated evaluation indicators is key to technology diffusion. Ecologically, the inhibition efficiency of carbonation return to the field on nitrogen and phosphorus leaching from the water column was quantified using a long period positioning test and the cumulative effect on microbial diversity was assessed. Economically, analyses the balance of farmer benefits, carbon trading potential and full life cycle costs [22]. Socially, combining carbonization of fields with desertification control to enhance regional carbon sink capacity.

Table 3: Research directions and key points in agricultural waste carbonization and returning to field

Research direction	Key point	Challenge	Potential breakthrough	References
Process optimization	The Effect of Temperature and Time on Carbides	The process is complex and difficult to scale up.	Simplify the process	[23]
Technology Integration	Optimize the return of regional resource data to the field	Data integration and device adaptation difficulties	Development of an intelligent integrated system	[24]
Soil application	Impact on various aspects of soil	The mechanism of action is unknown	Reveal the mechanism of action	[25]
Benefit Assessment	Greenhouse gases and carbon sinks	The evaluation system has not been unified	Establish an evaluation system	[26]
Industry development	Constructing an industrial chain and innovation model	High investment, low market recognition	High investment, low market recognition	[11]

7. Conclusions

In the context of global climate change and sustainable agricultural development. Carbonization of agricultural wastes to fields as an emerging technology. It shows great potential for improving soil quality, increasing crop yields and reducing environmental pollution. This study focuses on the ecologically fragile area of the agro-pastoral zone. The effect of carbonization of agricultural wastes on the prevention and control of water pollution and its key influencing factors were investigated. The

research results show that under the unique climatic conditions of the agricultural and pastoral intertwined zone, carbonization and return technology can all effectively reduce the loss of N, P and other pollutants in the water body. However, its effect is significantly affected by factors such as soil type, climatic conditions, and carbonization process parameters. For this region and sector, this study summarizes the key factors and applicable strategies. It provides a scientific basis for the popularization and application of carbonization technology.

Carbonized return technology is strategically important in green agriculture and water conservation. It can not only realize the resourceful use of agricultural waste and reduce environmental pollution, but also improve the soil structure, enhance soil fertility and promote the sustainable development of agriculture. In the future, policy guidance and technology research and development should be further strengthened. Promote the popularization and application of carbon-based field-returning technology in the agricultural and pastoral intertwined zones and even in a wider region. It will provide strong support for the achievement of the goals of green agricultural development and ecological civilization. Although this study has achieved some milestones, there are still some limitations. For example, there is a lack of systematic monitoring of the long-term effects of carbonization and field return technologies under different climatic conditions, and the optimization of carbonization process parameters has not been studied in sufficient depth. Future research should focus on the following aspects: a. Strengthen long-term positioning tests to systematically assess the impact of carbonization technology on multi-media environment, such as soil, water, atmosphere, etc.; b. Develop high-efficiency and low-consumption carbonization process to improve the stability and environmental safety of carbonization products; c. Explore the coupling effect between carbonization technology and other agricultural waste resource utilization technologies, and build a model of recycling agricultural waste; d. Strengthen policy guidance and financial support to promote the industrialization of carbonization technology; and e. Promote the industrial development of carbonization technology and the development of agricultural waste. d. Strengthen policy guidance and financial support to promote the industrial development of carbonization technology. It is believed that through the collaboration and joint efforts of many parties, carbonization technology will make greater contributions to the sustainable development of agriculture and the construction of ecological civilization.

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