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Unlocking the Potential of Biochar Based Slow-Release Fertilizers: a Systematic Review

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A B S T R A C T

Traditional fertilizer application methods are inefficient and environmentally harmful. Biochar releases nutrients gradually, providing a steady supply to plants while reducing leaching and runoff. Additionally, biochar enhances soil physical properties, such as water retention and structure, leading to improved fertility and plant growth. To fully understand the potential of biochar-based slow-release fertilizers, a systematic review is proposed. The study aims to assess their effectiveness, understand underlying mechanisms, and identify limitations or challenges. It selected studies that investigate biochar-based fertilizers and their effect on the plant growth, nutrient release, and soil fertility. Understanding these production methods is crucial for optimizing the characteristics of biochar-based fertilizers. Overall, this review contributes to the development of sustainable agricultural practices.

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INTRODUCTION

Agricultural practices play a crucial role in meeting the global demand for food, feed, and fiber. However, traditional fertilizer application methods often result in inefficient nutrient utilization and adverse environmental effects (Lal, Nayak, Kumar, & Kumar, 2022). Nutrient leaching, volatilization, and runoff can lead to water pollution, eutrophication of water bodies, and the loss of valuable nutrients from agricultural systems (Guo et al. 2022). In recent years, biochar has emerged as a potential solution for improving nutrient management in agricultural systems. Biochar is a carbon-rich material produced through the process of pyrolysis, which involves heating organic biomass, such as crop residues, wood chips, or animal manure, in a low-oxygen environment.

Biochar possesses several unique properties that make it attractive for agricultural applications. It has a high surface area, porous structure, and negative surface charge, which enable it to adsorb and retain nutrients, such as nitrogen, phosphorus, and potassium (Luo, 2023). These nutrients are slowly released over time, providing a steady supply of nutrients to plants and reducing the risk of leaching and nutrient runoff (Finalis et al. 2020). Biochar-based nano-fertilizer offers greater prospects of reducing nutrient leaching, improving water retention, and improving plant nutrient and water use efficiency (Das & Ghosh, 2021). The slow release nature of biochar-based fertilizers also enhances nutrient use efficiency, ensuring that a larger proportion of applied nutrients is taken up by plants, thereby reducing the need for frequent fertilizer applications. Biochar-based fertilizers can improve soil characteristics by slowing the rate of nitrogen release (Sim 2021; Nguyen 2021; Khajavi-Shojaei, 2023).

Furthermore, it has been discovered that biochar enhances the physical characteristics of soil, such as water-holding capacity and soil structure, leading to enhanced soil fertility and plant growth (Afaf, et al. 2023). It also acts as a habitat for beneficial soil microorganisms, promoting microbial activity and nutrient cycling. Additionally, biochar can contribute to carbon sequestration by locking away carbon dioxide captured during biomass pyrolysis, potentially mitigating climate change effects. According to Bhatt, Buddhi, & Suthar (2023), biochar-based slow-releasing fertilizers have received recommendations for the effective management of soil nutrients and the promotion of crop growth.

The findings of this review will provide a comprehensive understanding of the current state of knowledge, identify research gaps, and offer insights for optimizing the formulation and application of biochar-based fertilizers. Ultimately, this study will benefit in the creation of environmentally friendly agriculture methods that enhance nutrient management, improve crop productivity, and minimize the environmental impacts associated with conventional fertilizer use.

LITERATURE REVIEW

Biochar based Fertilizer

Biochar has many benefits, including enhanced plant growth and soil properties, control of plant diseases, bioremediation, wastewater treatment, and application as a support material for enzyme immobilization (Chausali, Saxena, & Prasad, 2021). In terms of the effects of biochar on plant, various approaches have been recommended. Amendments enable a high production of safe food while significantly reducing the need for commercial inorganic fertilizers, which reduces environmental pollution (Rombel, Krasucka, & Oleszczuk, 2021).

Furthermore, biochar was found to be safe and environmentally friendly for soil application, and it tended to increase stem and root length, fresh and dry weight at low doses (0.5 wt%). The current study could serve as a model for addressing eutrophication and P deficiency issues (Ren et al., 2021). Compared to unenriched biochars, enriched biochars with enhanced physicochemical properties improve soil biological, physical, and chemical properties, as well as plant growth and yield (Ndoung, Figueiredo, & Ramos, 2021).

Biochar can retain N availability, boost residual effects, and improve plant N uptake efficiency (Barbosa, Correa, Carneiro, & Melo, 2022). Biochar demonstrated promising properties and could be utilized as a potential fertilizer on slow release for sustainable and green agriculture applications (Khan et al., 2021). Bhatt, Buddhi, & Suthar (2023) indicated that biochar-slow release fertilizers has numerous advantages for the environment and can be used to optimize soil-plant nutrients. Slow-release fertilizers (SRFs) help release nutrients slowly over a long period of time (S. Yang, Xiao, Liang, & Tan, 2023).

In addition to improving crop yields, the use of biochar fertilizer has the potential to mitigate climate change by reducing greenhouse gas emissions and improving soil carbon sequestration. The application of biochar fertilizer can provide a sustainable and cost-effective solution to the challenge of increasing agricultural productivity while minimizing environmental impact.

Slow-release fertilizers (SRFs)

Slow-release fertilizers (SRFs) made with biochar are a sustainable and environmentally friendly approach to nutrient management in agriculture (Firmanda, Fahma, Syamsu, Suryanegara, & Wood, 2022). Biochar is a carbon-rich material derived from the pyrolysis or thermal decomposition of organic matter, such as wood, crop residues, or other biomass.

Biochar acts as a physical barrier that slows down the release of nutrients into the soil (Dinh, 2022) . This gradual release aligns nutrient availability with plant demand, reducing the risk of nutrient losses due to volatilization or leaching. This is particularly important in sustaining plant growth over an extended period.

SRFs made with biochar can reduce the need for frequent applications of conventional fertilizers. This can result in cost savings for farmers and a decreased environmental impact associated with fertilizer use. slow-release fertilizers made with biochar have the potential to improve nutrient management in agriculture, reduce environmental impacts, and enhance soil health. They represent a promising approach for sustainable and environmentally responsible farming practices.

METHODOLOGY

This systematic review used specific inclusion and exclusion criteria to select relevant and reliable studies. Inclusion criteria included peer-reviewed studies on biochar-based slow release fertilizers' effects on plant growth, nutrient release, and soil fertility, conducted in various agricultural systems and written in English. Exclusion criteria encompassed studies unrelated to biochar-based slow release fertilizers, those focusing solely on biochar production methods, studies with insufficient data or incomplete methodologies, and non-peer-reviewed sources. Boolean operators “biochar AND Fertilizer AND Slow release” was used to search results in Harzing’s Publish or Perish System. This data was used to identify the number of articles and Citations in the Recent 10 Years based on the Scopus Database. Identified studies will be screened based on titles and abstracts. The remaining studies will undergo a full-text assessment to determine eligibility for inclusion, adhering to the research objectives.

RESEARCH RESULT AND DISCUSSION

Biochar Production and Properties

Biochar is produced through the process of pyrolysis, which involves heating organic biomass in a low-oxygen or oxygen-free environment. Various biochar production methods exist, each with its advantages, limitations, and resulting biochar properties.

The traditional kiln method involves heating biomass in a simple kiln or pit with limited control, while improved combustion systems use specialized kilns or stoves to enhance efficiency and reduce emissions. Continuous pyrolysis systems, designed for large-scale production, employ conveyor belts or augers to optimize process parameters and achieve improved biochar yield and quality. Slow pyrolysis, with lower temperatures and longer residence times, maximizes biochar production and minimizes bio-oil and gas formation, typically suitable for small-scale operations. Fast pyrolysis, operating at higher temperatures and faster rates. Hydrothermal carbonization mimics coal formation under high temperatures and pressure with water, enabling the conversion of diverse feedstocks and processing of wet biomass. Each method offers unique advantages and limitations, providing options for different scales, feedstocks, and desired biochar properties.

It is important to note that the choice of biochar production method can significantly influence the properties and performance of biochar for slow release fertilizer applications (Mishra et al., 2023; Marcińczyk, 2022). Factors such as feedstock selection, temperature, heating rate, residence time, and oxygen availability during pyrolysis all play a role in determining the resulting biochar's physical, chemical, and nutrient retention properties.

The high surface area and porous structure of biochar facilitate effective nutrient adsorption and retention, enabling a controlled release of nutrients over time (Khajavi-Shojaei et al. 2020). Additionally, biochar exhibits the capacity to adsorb and retain nutrients, including nitrogen, phosphorus, and micronutrients, through chemical bonding and electrostatic interactions, thereby preventing nutrient leaching and ensuring their availability for plant uptake. The stability and high carbon content of biochar promote its long-term persistence in the soil, allowing for sustained nutrient release (Shaon Kumar Das et al. 2023). Moreover, biochar's alkaline nature can influence soil pH and buffering capacity, thereby affecting nutrient availability and regulation of soil pH levels (Purakayastha et al. 2019). By mitigating soil acidity or alkalinity, biochar creates a favorable environment for optimal plant growth.

Table 1. Various Biochar Production Methods, Advantages, and Limitations

References	Biochar Production Method	Description	Advantages	Limitations
(José et al. 2019)	Traditional Kiln Method	Combustion of biomass in a traditional kiln	Simple and low-cost	Inconsistent biochar quality
(Adeniyi, Ighalo, & Onifade 2021)	Improved Combustion Systems	Advanced systems like gasifiers and retort kilns	Better control of temperature and oxygen levels	Higher initial investment cost, complexity
(X. Shen et al. 2022)	Continuous Pyrolysis Systems	Systems like rotary kilns and fluidized bed reactors	Continuous operation, higher production capacity	More complex setup, higher operational requirements
(de Almeida et al. 2022)	Slow Pyrolysis	Heating biomass at low temperatures with slow heating rates	High carbon content, nutrient retention	Longer processing time, lower production capacity
(Robert & Braghiroli 2022)	Fast Pyrolysis	Heating biomass at high temperatures with rapid heating rates	Higher surface area, porosity	Lower carbon content, less stable biochar
(Xu et al., 2022); Mariuzza et al., 2022)	Hydrothermal Carbonization	Treatment of biomass with high-pressure steam at elevated temperatures	Unique properties, higher moisture content	Lower carbon content, different nutrient retention characteristics

Slow Release Mechanisms

Biochar-based fertilizers possess unique properties that make them effective in managing nutrients. One key feature is the high surface area and porosity of biochar, which enables it to adsorb nutrients onto its surface. Moreover, biochar's surface chemistry allows for ion exchange, where nutrient cations bound to the biochar can be exchanged with other ions in the soil solution. This mechanism facilitates the slow release of nutrients, providing a consistent supply to plants over time. Luo (2021) found that the release of nitrogen from biochar fertilizer enriched with magnesium was influenced by various factors associated with the biochar carrier, such as hydrogen bonding, the confinement effect, and electrostatic attraction for NH4+. Additionally, the findings of a study by (Hong et al. 2020) confirmed that biochar with a more hydrophilic surface released higher amounts of nutrients and organic matter through leaching compared to biochar with a predominantly hydrophobic surface.

In addition to adsorption and ion exchange, biochar's micropores and mesopores physically trap nutrients within its structure. Acting as reservoirs, these pores store nutrients and gradually release them as the surrounding soil solution becomes depleted. Furthermore, biochar can influence the speciation of certain nutrients, modifying their availability for plant uptake. The physical entrapment of urea within the biochar micro- and nanopores stabilizes it within the SRF pellets (Bakshi, 2021).

The physical and chemical properties of biochar significantly influence nutrient release (Zhang, Wang, & Feng, 2021). Surface area, pore size distribution, porosity, and nutrient adsorption capacity all determine how effectively biochar retains and releases nutrients. Soil characteristics, including pH, moisture content, and microbial activity, can impact the rate at which nutrients are released from biochar. Finally, environmental conditions like temperature and rainfall patterns play a role in nutrient release from biochar (Wang et al. 2020).

Crop Growth and Yield Responses to Biochar-Based Fertilizers

The slow and continuous nutrient release pattern aligns with the nutrient requirements of plants, reducing the risk of nutrient imbalances and optimizing nutrient uptake efficiency. Biochar enhanced water-holding capacity under higher evaporation stress than compost (Ghorbani et al. 2023). Biochar's ability to improve soil structure, porosity, and water-holding capacity contributes to enhanced root development and nutrient uptake (Adekiya et al. 2020). The increased availability of essential nutrients provided by biochar-based fertilizers promotes vigorous plant growth, leading to improved crop yields. Additionally, biochar-amended soils have been found to exhibit improved nutrient retention and reduced nutrient losses, which further support crop growth and yield.

Biochar-based fertilizers offer several advantages in terms of nutrient use efficiency and reduced environmental impacts. The controlled release of nutrients provided by biochar minimizes nutrient losses through leaching, runoff, and volatilization, ensuring that a higher proportion of applied nutrients is utilized by plants. This increased nutrient use efficiency leads to improved crop productivity and reduced fertilizer requirements, resulting in cost savings for farmers.

As it is presented in Table 2, biochar can lead to increased crop yields. It is worth noting that the effects of biochar on crop growth can vary depending on factors such as biochar type, application rate, soil conditions, climate, and crop species.

Table 2. Effects of Biochar on Plant Growth

Feedstocks	Crops/Plants	Biochar Percentage (by Vol.)	Effects	References
Coconut shells	Maize	-	Increased the grain weight and yield	(Y. Yang, Zhou, Hu, & Lin, 2020)
-	Rice seedlings	400 mg kg−1 of nano-BC	The biomass of the seedlings increases by 435%	(Y. Shen et al., 2020)
-	Chinese white cabbage	20 g ·kg−1 biochar + 10 g ·kg−1 nano-zeolite	Improved the plant growth	(Feng et al., 2022)
Stevia leaf extract	Groundnut	4 kg ha-1 and 10 kg ha-1	Significantly influences the growth, uptake, and yield	(Kavitha, Prasad, & Giridhara, 2022)
Rice straw	Canola	50 mg kg− 1	Significantly improved yield and plant height	(El-shahawy et al. 2022)
Corn stalk and rice husk	Rice	6 t ha−1	A substantial effect on the amount of chlorophyll, plant height, leaf area index, and yield	(Elshayb et al. 2022)
Rice husk	Rice		a significant increase in grain yield	(Sheikhnazari et al. 2023)
Acer pseudoplatanus L.	Safflower and mint plants	25 g biochar kg−1 soil)	Increased plant height, shoot biomass, root length, and mass	(Farhangi-Abriz & Ghassemi-Golezani 2023)

Challenges and Future Directions

Analyzing the data over 10 years can help identify growth trends in research on biochar application. The bar chart (Fig. 1) shows that the highest number of articles related to biochar-based slow release fertilizers were published on Scopus in the year 2022, with a total of 53 articles, while the highest number of citations occurred in the year 2017. Based on the information from litmaps (Fig 2.), it can be determined that the article with the highest number of citations is indicated by a larger circle size, while the latest research on biochar is conducted by (Bhatt et al. 2023; Liu 2023). Assessing the number of citations can indicate the impact and influence of research on biochar application.

Further research is needed to elucidate the specific processes involved in nutrient adsorption, desorption, and release from biochar, as well as the factors influencing these interactions. While progress has been made in studying biochar-nutrient interactions, there are still knowledge gaps to be addressed. Additionally, most studies have been conducted under controlled laboratory or greenhouse conditions, and there is a need for more field-scale investigations to assess the real-world applicability of biochar-based fertilizers. There are opportunities for further investigation and optimization of biochar-based fertilizers.

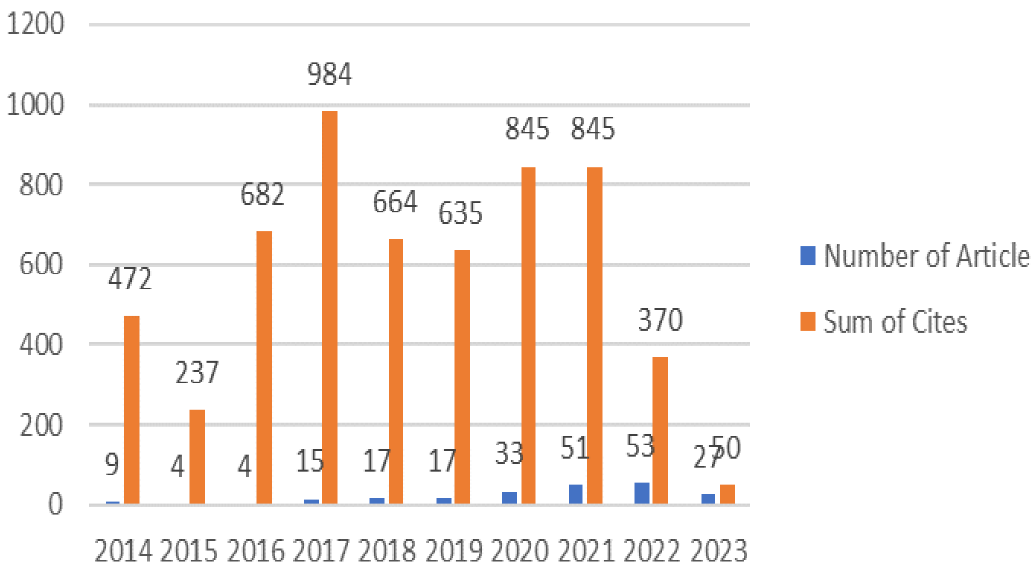

Figure. 1. The Number of Articles Published and Citation in Recent 10 Years based on Scopus Database (2014 – 2023).

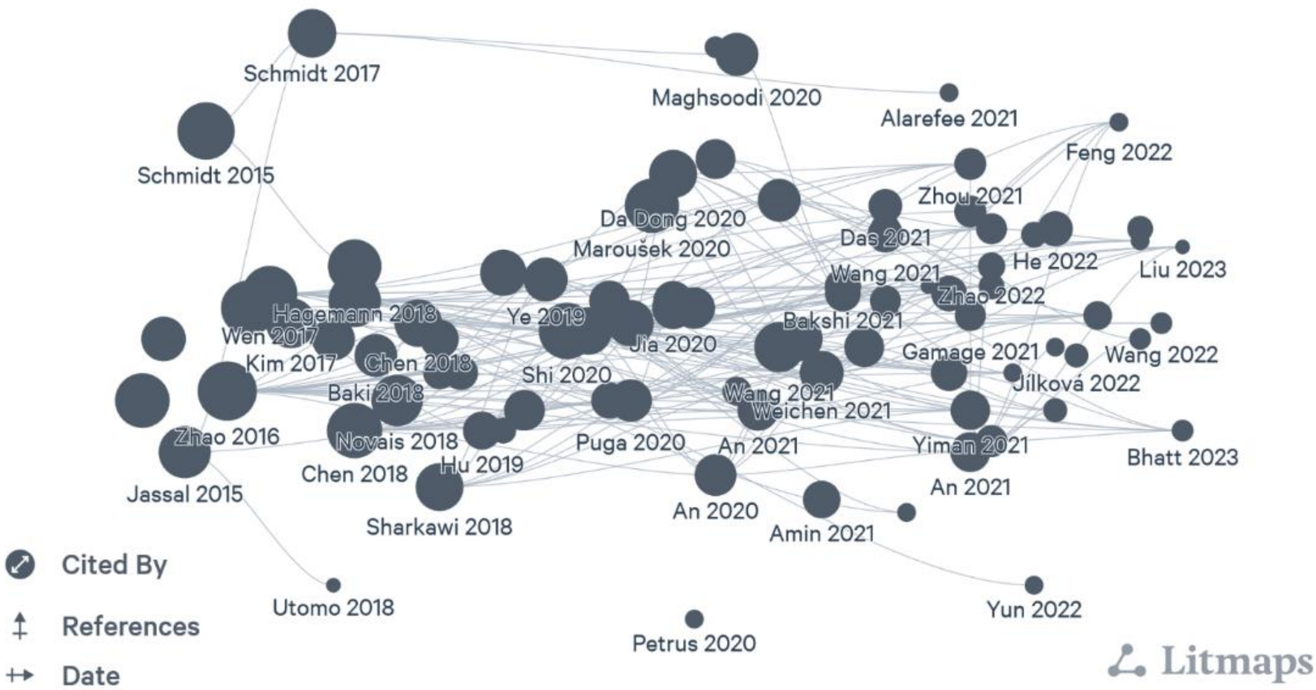

Figure. 2. A Map in The Distribution of Biochar-Based Slow Release Fertilizers Literature on Scopus Database

CONCLUSIONS AND RECOMMENDATIONS

In this systematic review of biochar-based slow release fertilizers, several significant findings have been uncovered. Biochar possesses essential properties such as high surface area, porosity, cation exchange capacity, and nutrient adsorption capability, which make it well-suited for slow release fertilizer applications. Secondly, the characteristics of biochar are heavily influenced by factors such as the chosen production method, feedstock composition, and pyrolysis conditions, affecting its carbon content, stability, nutrient retention capacity, and release characteristics. Thirdly, biochar-based fertilizers employ various mechanisms such as adsorption, ion exchange, micropores, and chemical reactions to retain and gradually release nutrients, leading to efficient nutrient management and reduced nutrient losses. The recommendation is to prioritize environmentally friendly and efficient methods of fertilization, like biochar-based slow-release fertilizers, as part of broader efforts to improve agricultural sustainability.

ADVANCED RESEARCH

There may be challenges or obstacles associated with using biochar-based fertilizers in real-world agricultural practices. Advanced research could explore innovative manufacturing techniques to enhance the quality and consistency of biochar products.

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