Journal of Technology and Value Addition, Volume 7 (1), January 2025: (01-29)

Review Article

Multifaceted Role of Biochar in Sustainable Rice Cultivation: A Short Review

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Abstract

Biochar, a carbon rich product derived from biomass pyrolysis process, has emerged as a promising and sustainable soil amendment with potential to enhance rice cultivation while mitigating environmental issues such as soil deterioration, nutrient depletion and greenhouse gas emission. In this review, the preferred reporting items for systematic reviews and meta-analyses (PRISMA) principles were followed to ensure methodological consistency and transparency. A comprehensive literature search was conducted to include studies published from 2013 to 2024, using major research databases. Relevant research and review papers were thematically grouped to highlight the patterns, outcomes, and research gaps linked to the use of biochar in rice production systems. These studies and the variables measured were used to achieve the objectives of the review. This review paper emphasizes the multifaceted benefits of biochar application on rice farming focusing on the role of biochar enhancing soil physical and chemical properties, nutrient retention, and overall crop productivity. The application of biochar significantly improves soil structure by increasing soil aggregation, enhancing water-holding capacity and aeration. Additionally, biochar increases cation exchange capacity of the soil, which reduces nutrient leaching and enhances the availability of essential nutrients such as silicon (Si), potassium (K), and phosphorus (P). Additionally, the application of biochar plays a crucial role in climate change mitigation by reducing greenhouse gas emissions, particularly *nitrous oxide and methane. Changes in microbial activity, nitrogen cycling, immobilizing heavy metals and nutrient use efficiency are also beneficial effects of the application of biochar. However, further research on biochar properties, rate and type of biochar application for different soil types and rice varieties, and effects on long term application are required to maximize the positive effects of application of biochar in rice farming.*

***Keywords**: Biochar, Greenhouse gases, Rice, Soil alteration, Sustainability*

1. Introduction

Rice is the main staple food, especially in Asian countries, where over 90% of the world's rice is produced and consumed (Abeysekara and Rathnayake, 2024). Making rice as a vital crop for global food security, more than half of the world's population mainly in medium and low-income countries in Asia depends on rice as their primary food source, (Dhamira and Aminda, 2023). Therefore, with the continuously growing world the demand for rice is projected to increase by 60% in 2025 (Ali et al., 2020). Beyond its role as the primary energy source, rice provides livelihoods for millions of smallholder farmers in countries such as China, India, Indonesia, and Vietnam. (Hashim et al., 2024). These countries are among the top rice producers in the world.

However, there are many challenges such as high water usage, greenhouse gas emissions, soil degradation and nutrient depletion of soil in modern rice farming (Zhao et al., 2023). These challenges are emphasized the urgent requirement for sustainable solutions to ensure the rice production for future demands though conserving natural resources (Xie et al., 2015; Zhao et al., 2023). Application of biochar as carbon rich material has increased the significant attention as a potential solution to heal the environmental issues (Xie et al., 2015) and resilience (Figure 1). It can enhance the soil health, improve nutrient utilization efficiency, and reduce the rate of greenhouse gas emission, potentially transforming the sustainability of global rice cultivation (Zhao et al., 2023). There are many agricultural and environmental issues that threaten the long-term viability of rice cultivation system.

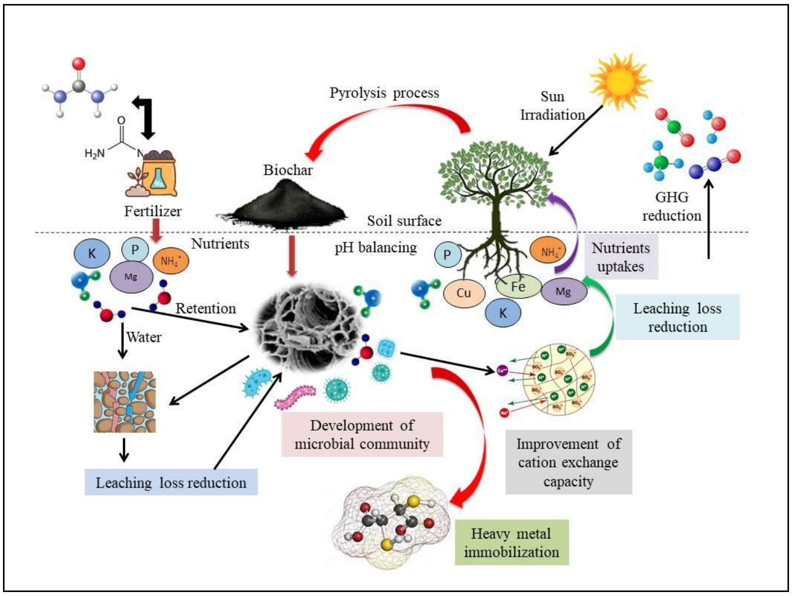
High water usage in traditional rice farming activities is one of the threat in the sustainability of the sector (Singh et al., 2018). Approximately 2,500 gallons of water are required to produce the one kilogram of rice grains, as fields are kept continuously flooded throughout the major growing season (Yaligar et al., 2017) mainly in lowland rice ecosystems. Apart from water usage, flooded paddy fields significantly contribute to greenhouse gas emissions, especially methane. Therefore, rice production is considered as one of the main causes of agricultural greenhouse gas emissions. Anaerobic decomposition of organic materials in the wet soils is considered as main cause of methene production in agriculture (Mboyerwa et al., 2022). The significantly higher capability to trap atmospheric infrared radiation by methene than the carbon dioxide make it as a potent greenhouse gas (Mikhaylov et al., 2020).

Soil degradation is another major challenge to sustainability for rice farming. It is believed that soil degradation is caused mainly due to heavy uses of chemical pesticides and fertilizers in intensive rice farming. The excessive use of nitrogen fertilizer reduces nitrogen use efficiency and creates environmental issues like ground water pollution, greenhouse gas emission and soil degradation (Ali et al., 2021).

The application of biochar has many positive impacts on soil health and rice cultivation (Lehmann et al., 2015; Ayaz et al., 2021). It is a valuable soil amendment (Asadi et al., 2021) with high amount of carbon. Therefore, biochar enables us to persist long period in the soil (Asadi et al., 2021). Several studies have shown that biochar can improve the physical and chemical properties of the soil, thereby improve soil structure, water holding capacity and aeration (Ali et al., 2020; Adebajo et al., 2022; Zhang et al., 2024). The porous structure of biochar also boosts microbial activity by providing habitats for soil microorganisms (Yin et al., 2021; Liu et al., 2024). Biochar can also trap nutrients and reduces nutrient leaching, allowing for gradual nutrient release that increases plant uptake over a longer period (Yin et al., 2021). Moreover, biochar indirectly reduce the greenhouse gas emissions related to fertilizer production and application, supporting global efforts to minimize agricultural emissions (Barman and Kandpal, 2019). These benefits are particularly valuable as intensive farming methods are commonly practiced for rice cultivation (Xie et al., 2015; Asadi et al., 2021).

However, despite the benefits several challenges curb application of biochar in rice cultivation, such as production costs, less awareness on the benefits of biochar among farming communities and the less research on sustainable application methods for different soil types and regions (Abukari et al., 2018; Hashim et al., 2024). To overcome these obstructions, collaboration among farmers, researchers, policymakers, and agricultural organizations is essential. Continued research on the long-term effects of biochar, advancement of pyrolysis technology and incentives for sustainable practices are essential for effective utilization of biochar for sustainable future of rice cultivation (Jaafar et al., 2015; Abukari et al., 2018) by ensuring food security for significant portion of world population while conserving the natural resources.

Figure 1: Application of biochar and in different ways to mitigate the environmental impacts with improving the soil



2. Materials and Methods

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) principles were followed in this review to ensure methodological consistency and transparency. An inclusive literature search was conducted to encompass publications from 2013 to 2024 using major academic databases such as Scopus, ScienceDirect, Web of Science, Google Scholar, and AGRICOLA. Boolean operators and relevant keywords, comprising "biochar," "rice," "paddy," "growth," "yield," "soil," "nutrient efficiency," and "greenhouse gas emissions," were used during the search process. Only unique, peer-reviewed research papers and original research articles written in English were considered. Studies assessing the impact of biochar application on rice cultivation in pot trials, greenhouse conditions, or field settings were included. Review papers, editorials, and original articles lacking primary data or direct relevance to the topic were excluded from the analysis. After the removal of duplicate records, all publications underwent a screening process. This included an initial screening based on titles and abstracts, followed by full-text reviews using predetermined inclusion and exclusion criteria. Data was extracted from each selected study, including information on biochar feedstock and characteristics, application rates and methods, experimental conditions, soil properties, rice varieties, and measured outcomes. These outcomes included soil fertility, crop yield, nutrient use efficiency, and greenhouse gas emissions. The methodological quality of the included studies was assessed using standard review procedures. Finally, the selected studies were thematically grouped to identify patterns, outcomes, and research gaps related to the application of biochar in rice production systems. These groupings helped analyze the measured variables in line with the objectives of this review.

1. Biochar production and characteristics

1.1 Process of biochar production through pyrolysis

Pyrolysis process involves the thermochemical decomposition of solid organic matters at high temperature; generally between 300 to 800 °C in anaerobic or very low amount of oxygen (Khater et al., 2024). Rice husk, rice straw, corn stalk, manure, wheat residues, wood and forestry byproducts are the common biomass used for biochar production (Spokas et al., 2012; Abrishamkesh et al., 2015; Barman and Kandpal, 2019; Asadi et al., 2021). Wood and forestry byproducts are more suitable to produce biochar with high carbon content, and which decompose slowly but have less nutrient content (Saarnio et al., 2013; Thomas and Gale, 2015). The major factor affecting the properties of biochar is temperature, however the heating rate and duration and source of carbon also have a significant impact on the properties of the end product (Asadi et al., 2021) (Table 01). The biochar produced at higher temperature (>600 °C) produces less yield with less nutrients, but high amount of ash, surface area (Xie et al., 2015; Asadi et al., 2021; Butnan and Vityakon, 2023) and more stable carbon compounds with resistant to decomposition (Lehmann and Joseph, 2009; Asadi et al., 2021) making them suitable for carbon sequestration. On the other hand, biochar produced under low temperature (300 to 500 °C) consists of a high amount of fertilizer, making them suitable to manage soil fertility (Asadi et al., 2021; Williams et al., 2023). Biochar produced under lower temperature also shows more porous structure (Asadi et al., 2021). Slow pyrolysis process with modest temperature and prolong residence time results higher biochar yield than rapid pyrolysis (Xie et al., 2015; Liu et al., 2016; Pahnila et al., 2023). Moisture content of the biomass also affects the final product properties as well as to the pyrolysis process (Asadi et al., 2021). Pre drying or cutting them into small pieces can improve the efficiency of the pyrolysis process. The cooling process after pyrolysis is also important to get maximum benefit of biochar. Cooling in oxygen free or minimum oxygen environments are important to prevent combustion after pyrolysis.

High carbon (C) contents of rice husk (RH) show a high potential of producing biochar (Lachke, 2002). Approximately 800,000 mt of rice husk is being produced annually in Sri Lankan rice milling process (AgStat 2016). Therefore, great potential existing to use this material as feedstock to produce the biochar under local conditions. According to Song and Guo (2012), were shown pyrolysis is often considered as the most feasible production process capable of yielding biochar having consistent and reliable product qualities suited to be used in agriculture. “Kunthaniya” is presently used by Sri Lankan farmers to produce rice husk biochar, and the product is often referred as the partially burnt paddy husk (PBPH). However, this technique doesn’t produce uniform products. Therefore, modifications to the process of pyrolysis are needed to assure the consistent output quality of the product. Modification of traditional Kunthainya has already been released as a technology for produce the biochar with obtaining sufficient amount of biochar yield.

Table 1: Chemical properties of rice husk biochar (RHB) prepared under different pyrolysis temperatures (Dissanayake et al., 2018).

Parameter	**RHB 350 ℃**	**RHB 500 ℃**	**RHB 650 ℃**
pH	7.48 ±0.04	9.11±0.01	9.38±0.02
EC (S/m)	0.01±0.00	0.05±0.00	0.06±0.00
Available P (mg/kg)	256 ±4	472±25	518±27
Available K (mg/kg)	5366 ±187	6525±548	7469±197
Available Mg (mg/kg)	150 ±13	247±14	300±5
Total P (%)	0.22±0.01	0.29±0.01	0.19±0.00
Total K (%)	0.57 ±0.03	0.69±0.03	0.75±0.04
Total Mg (%)	0.11±0.00	0.12±0.00	0.07±0.01
Total C (%)	45.4±1.6	47.8±1.5	50.0±0.8
Total N (%)	0.51±0.03	0.56±0.09	0.37±0.01

1.2 Physicochemical properties of biochar

Biochar offers beneficial effects for diverse environmental and agricultural management practices due to its diversity of physicochemical properties. The feedstock and pyrolysis conditions have significant impact on the characteristics of biochar (Pahnila et al., 2023). The elemental analysis of biochar produced from different feedstocks is shown in Table *2*. Higher surface area with abundant micro and macro pores and porosity play a significant role in various benefits of biochar (Ali et al., 2020, 2021; Hidayat et al., 2023; Pahnila et al., 2023). Porosity of biochar helps retain the water (Oladele et al., 2019; Ali et al., 2020, 2021), nutrients (Ali et al., 2020, 2021; Ning, 2022), and provide microbial habitats (Asadi et al., 2021), enhancing soil properties. Highly porous biochar structure can also improve soil aeration and drainage (Clough et al., 2013; Asadi et al., 2021). Biochar contains a significant amount of carbon, usually between 40 and 90% by mass (Adebajo et al., 2022; Gowthami et al., 2022). Adebajo et al. (2022) reported that the biochar produced from rice husk consists of approximately 50% carbon. This stable carbon may remain in soils for hundreds to thousands of years since it is not easily broken down by activities of microorganisms (Bi et al., 2021; Xu et al., 2022). Therefore, biochar is a useful method for carbon sequestration because of its carbon stability helping to slow down the climate changes by removing CO_2 from the atmosphere (Ding et al., 2022; Bo et al., 2023). Typically, biochar exhibit alkaline pH between 7 and 12, (Zhang et al., 2024) due to high ash content and basic cations like Ca^{+2}, Mg^{+2} and K^{+}. Therefore, biochar can be used to neutralize the acidic soils common in tropical regions and increase nutrient availability for plant growth (Barman and Kandpal 2019; Adebajo et al., 2022). Several studies reported that feed stocks with high lignin content and higher pyrolysis temperature tend to have higher pH (Xie et al 2015; Novak et al., 2019).

Table 2: Elemental analysis based on different feedstock

Feedstock	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	Reference
Rice straw	34.24	3.31	1.50	37.06	Babiker et al., 2020
Wheat straw	70.06	3.50	1.50	37.60	Qayyum et al., 2020
Soft wood	22.67	1.31	3.04	72.99	Singh and Chandra, 2019
Hard wood	53.66	1.83	1.24	42.98	Ayaz et al., 2021
Orange feels	40.43	4.83	1.56	52.90	Amalina et al., 2022
Date palm leaflets	43.14	7.49	0.20	52.70	Hamad and Idrus, 2022

1.3 Influence of pyrolysis temperature on biochar characteristics

Pyrolysis temperature mainly affects biochar characteristics like yield, surface area, ash content and stability (Hidayat et al., 2023). Higher pyrolysis temperatures lead to more ash content which reduces the biochar yield (Butnan and Vityakon, 2023). Table 3 shows different pyrolysis techniques and biochar yield. Higher pyrolysis temperatures increase volatilization of organic matter remaining high amount of ash. This biochar is suitable as a soil amendment (Butnan and Vityakon, 2023) for acidic soils. However, higher ash content can lead to salt stress and nutrient imbalances of the soil (Butnan and Vityakon, 2023). Higher temperatures (600 - 800°C) create voids and channels within the biochar structure by thermal decomposition of organic matter (Ali et al., 2022). This porous structure increases the surface area and is the key factor of the higher absorption capacity of nutrients and contaminants (Asadi et al., 2021). However, higher pyrolysis temperature led to loss volatile nutrients like nitrogen, sulfur, and potassium (Lehmann and Joseph, 2009; Verheijen et al., 2010). Therefore, the pyrolysis temperature should be carefully decided according to the purpose of the application of biochar.

Table 3: Different pyrolysis techniques and biochar production

Pyrolysis technique	Temperature (°C)	Time	Biochar (%)	Reference
Slow	300 - 550	hours to day	35	Shahbaz et al., 2020
Intermediate	450 - 550	10 - 20 s	25	Daful and Chandraratne, 2018
Fast	450 - 600	10 - 1000 s	12	Thomas et al., 2019
Hydrothermal	< 200	1 - 16 h	35	Brown et al., 2020

1.4 Distinct properties of the rice husk biochar

Typically, a high amount of silicon and ash content than the biochar derived from other feedstock can be taken as the distinct qualities of rice husk biochar. Rice husk naturally consists of a high amount of SiO_2 (Asadi et al., 2021; Butnan and Vityakon, 2023) and during the pyrolysis process this SiO_2 may retain in the biochar, contributing its unique properties. The silicon content of rice husk biochar may reach around 15 - 20% or more (Adebajo et al., 2022). Therefore, adding rice husk biochar in rice cultivation is important as silicon plays a vital role in rice plant growth and development (Karam et al., 2022). The ash concentration of rice husk biochar ranges between 2 - 8% (Asadi et al., 2021; Butnan and Vityakon, 2023).

This ash content is a direct result of the inorganic minerals of the rice husk. There are both merits and demerits of high amounts of ash content of rice husk biochar. Soil pH adjustments, nutrient supply and improving soil physical properties can be taken as merits, while salinity stresses and nutrient imbalances are the demerits of high amount of ash in rice husk biochar (Asadi et al., 2021; Butnan and Vityakon, 2023). Due to the high ash and silicon content of rice husk biochar, a synergistic effect can be obtained by the application of rice husk biochar in rice cultivation.

2. Impact of biochar on soil properties

2.1 Influences on soil physical and hydraulic properties

Biochar mainly affects several soil physical properties like water retention, bulk density and soil structure. The porous nature of the biochar creates extra spaces to hold water. The advantage of this practice is particularly pronounced in the sandy or collapsed soils which naturally face many challenges related to the low water holding (Barman and Kandpal, 2019; Karam et al., 2022). Through enhancing the soil moisture content, biochar diminishes the frequency and quantity of irrigation required, thus proving particularly useful in areas susceptible to drought or water scarcity (Armynah et al., 2018; Rawat et al., 2019). The application of biochar has been demonstrated to decrease (3 - 8%) the soil bulk density, particularly when utilized in substantial amounts (Ahmad et al., 2022). Reduction of bulk density enhances soil aeration and promotes root penetration which enables plant roots to more efficiently access the vital nutrients and water (Lehmann et al., 2015; Oladele et al., 2019). The enhancement of soil structure is essential for increasing crop growth, yields, and resilience. The incorporation of biochar to the soil promotes soil accumulation which resulted to improve the structural integrity (Qian et al., 2014; Lehmann and joseph, 2009). Biochar encourages the development of stable soil aggregates which enhance the porosity and aeration (Rawat et al., 2019). This enhanced aggregation not only helps mitigate soil erosion but also facilitates better water infiltration into the soil profile (Lehmann et al., 2015). Such advancements in soil structure are critical for establishing an environment that supports robust crop growth, especially for rice.

2.2 Impact of chemical properties of biochar on soil substrate

The alkaline nature of the biochar significantly increases the pH of paddy soil. Many dynamic nutrients become more accessible to the plants within ideal pH range of around 6 to 7 which making this amendment is important for improve the nutrient availability (Lehmann et al., 2015; Ahmad et al., 2022). Increasing of the soil pH with application of biochar promotes the healthy plant growth which enhances the bioavailability of many of key nutrients such as calcium, magnesium, and phosphorus (Liang et al., 2014). This adjustment may lead to increase the crop yields and improved soil health and fertility through balancing the soil acidity (Singh et al., 2018). Moreover, the cation exchange capacity (CEC) which is the soil ability to hold and supply the positively charged ions such as calcium, magnesium, potassium, and ammonium to plant roots is greatly enhanced by 2.1, 5.6, 8.2, 11.58% when biochar is incorporated into the soil (Xie et al., 2015). By enhancing the surface area available for cation adsorption, biochar's porous makeup helps the soil to retain vital nutrients. More stable supply of nutrients over long period was possible through higher CEC which also lessens nutrient leaching (Zhang et al., 2024). In terms of preserving soil fertility and raising agricultural output, this is very advantageous. Adding biochar to the soil has been demonstrated to improve the availability of vital nutrients (Xu et al., 2022). Because of the ability to absorb nutrients and release them gradually, biochar helps to reduce nutrient runoff and allows more consistent nutrient supply for plant roots (Singh et al., 2018; Ullah et al., 2018; Xie et al., 2015). Higher plant vigor and productivity of rice crops are the results of improved nutrient availability (Xie et al., 2015; Tsai and Chang, 2021; Xu et al., 2022).

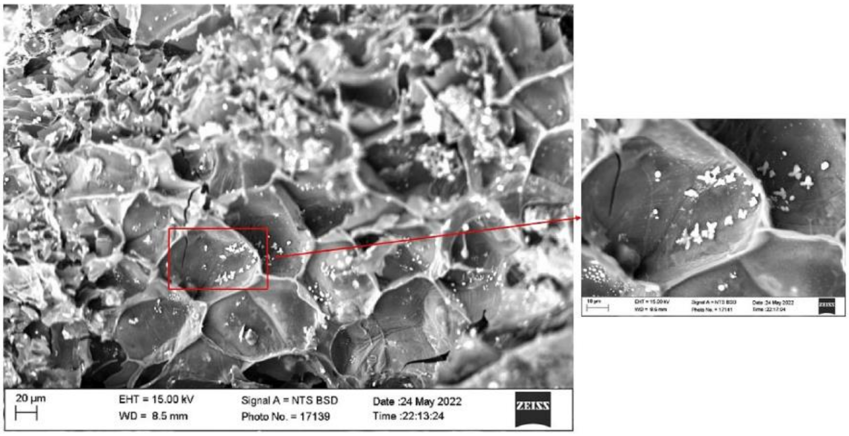
2.3 Contribution to favorable environment for rice growth

Applying biochar to the soil can alter its physical and chemical properties, enhancing conditions for rice growth and nutrient absorption (Ali et al., 2020). The incensement of water holding capacity of paddy soil resulted by the biochar application which ensures enough water in rice plants, particularly during the critical growth phases. Moreover, the enhancements in CEC and nutrient availability enable rice plants to access the necessary nutrients more efficiently from paddy soil which promotes the healthier growth and higher yields (Xiang et al., 2017; Rawat et al., 2019). Enhanced soil aggregation and reduced bulk density helps promote the enhanced root penetration and growth (Lehmann et al., 2015). A plant with robust root growth is more resilient to stress, which improves crop performance with treatment of biochar. Through enhancing the soil structure and nutrient availability consequence on lessen impact on abiotic stresses such as nutrient deficiencies and drought (Xie et al., 2015). The improved qualities of the soil help to provide a more stable growing background which encourages steady yields.

3. Biochar and nutrient management of rice cultivation

Nutrient management of rice cultivation though promoting both agronomic efficiency and environmental sustainability has arisen as an essential implement (Thomas and Gale, 2015). As a substantial soil amendment, biochar improves the nutrient retention which increases the nutrient availability and reduce the nutrient leaching (Zavalloni et al., 2011). These benefits can contribute to more sustainable and effective rice farming practices. Biochar enhances the nitrogen fertilizer use efficiency, availability and uptake of essential nutrients which mitigates the nutrient pollution in rice fields. Biochar can adsorb the ammonium (NH_4^+) and lessen nitrate (NO_3^-) leaching because of its porous structure which increases the surface area for chemical molecule interactions (Saarnio et al., 2013; Yin et al., 2021). The porous structure of the biochar can create a favorable habitat for soil microorganisms that helps convert the nitrates into less mobile forms (Figure 2). Moreover, higher cation exchanging capacity (CEC) of biochar improves the retention of positively charged ammonium ions which prevent the washed away by leaching (Lehmann et al., 2015; Tsai and Chang, 2021). Investigation has indicated that the additions of biochar can result in a notable increase in the amount of nitrogen in the soil. The necessity of frequent nitrogen fertilizer application can be decrease by this improvement in N retention capacity of soil which makes it possible to better synchronize nitrogen release and plant uptake (Ahmad et al., 2022). In addition to its positive effect on nitrogen management, the application of biochar is essential for enhancing the availability and absorption of vital minerals for rice production, including silicon (Si), potassium (K), and phosphorus (P) (Yin et al., 2021; Tan et al., 2024). Rice yields may be limited by deficits caused by phosphorus which frequently found in the soils in forms that are not easily absorbed by plant roots (Jaafar et al., 2015). Application of biochar showed increased availability of more phosphorus. Because of the large specific surface area, biochar can adsorb more phosphorus ions, which help reduce the amount of P since poor fixing with soil particles and formed the unstable compound or electrostatic attractions. As a result, rice plants have easier access to the soil solution with higher concentration of available phosphorus (Xie et al., 2015; Xu et al., 2022). The presence of biochar inspires the growth of beneficial microbial communities in the soil which can further increase the availability of phosphorus to plants by solubilization.

Figure 2: SEM image of bacterial colonization over the surface of biochar (Bolan et al., 2023)



4. Biochar and rice yield

Application of paddy husk biochar in agricultural system has increased the potential to enhance the crop growth and yield particularly in rice cultivation (Zhang et al., 2024). Experiments have demonstrated the yield increases ranging from 10 to 30% with application of biochar, particularly when combined with the fertilizers (Xie et al., 2015). Biochar enhances soil properties, such as improved nutrient retention, increased water-holding capacity, and enhanced microbial activity, which cooperatively contribute to the better plant growth and high yield (Singh et al., 2018; Luo et al., 2021). According to some experimental outcome, the application of biochar on rice yield has slightly no effect during the initial seasons. However, meta-analysis of several field tests, for instance, showed that whereas biochar usually enhanced soil quality, its impact on rice yield output which differed greatly depending on the area and farming technique (Xiang et al., 2017). Applying too much amount of biochar creates detrimental effects including changing the chemistry of the soil or immobilizing nutrients, while applying too little amount may not have enough beneficial effects. Ideal application rate of biochar must be determined to obtain the most efficient yield outcome of rice cultivation system (Oladele et al., 2019; Ning et al., 2022). The application of biochar and rice yield has a complicated and nuanced relationship. Even though a lot of research suggests that biochar can increase the rice yields in specific situations, it is important to understand that its efficacy is not assured and can differ greatly depending on several variables (Lai et al., 2017). The vigor and output of plants is directly correlate to improved soil health (Zhang et al., 2024). Through retaining and releasing the nutrients gradually with application of biochar helps to plants absorb the nutrients at the right times, especially during critical growth phases (Tan et al., 2024). This can result in improved growth and increased yields particularly when biochar was combined with other fertilizers (Yaligar et al., 2017; Selvarajh et al., 2024). By increasing the plant's ability to retain water, the application of biochar can contribute to rice plants to adapt to drought or water level variations which resulted in consistent yields.

5. Biochar and greenhouse gas (GHG) emissions

While nitrogen fertilization application and microbial activity impacted to nitrous oxide productions and methane emissions from rice fields under anaerobic conditions, which is typical in flooded paddy systems (Brahima et al., 2017). Through variations of soil conditions and microbiological activity with addition of biochar to rice fields have demonstrated the considerable reduction of greenhouse gas production, especially methane emissions from rice fields can be significantly reduced by applying biochar as soil amendment (Singh et al., 2017). Likewise, it has been discovered that biochar diminishes N_2O emissions (Oo et al., 2018). Although the relationship among soil microbes, nitrogen fertilizers, and optimum rate of biochar is complicated, there evidences on assistance and control of the nitrogen cycle by biochar in ways that lower the formation of N_2O. Especially in waterlogged environments, the porous nature of biochar enhances the soil aeration which lowers the methane generation (Zhao et al., 2023). It was demonstrated that biochar reduces the methane emissions by increasing the number of aerobic bacteria and inhibiting methanogenic archaea (Singh et al., 2017). Enhancement of nitrogen transformation mechanisms through enhanced aeration caused lowering the N_2O output. Advantageous soil microorganisms can be found in biochar, and they can affect the structure of the microbial community and the soil metabolic processes (Srivastava et al., 2023). Moreover, the interactions between biochar and nitrogen cycling microbes may enhance the nitrogen use efficiency which minimizes the nitrous oxide emissions (Saarnio et al., 2013). By improving nutrient retention and availability, biochar can optimize the use of nitrogen fertilizers through reducing the excess nitrogen. Effective nitrogen management can also minimize the need of chemical fertilizers which leads to further reductions in GHG emissions associated with fertilizer production and application in paddy fields.

6. Biochar and heavy metal immobilization

Heavy metals like cadmium (Cd), lead (Pb), arsenic (As) and mercury (Hg), can accumulate in rice plants making the serious health concerns to consumers (Liang et al., 2021). Immobilizing of heavy metals in contaminated soils through the use of biochar has shown promise in lowering the amount of these metals that rice plants absorb (Hoang et al., 2024). Concern over heavy metal contamination with rice can be seen commonly in areas where mining, industrial operations, and inappropriate waste disposal. Heavy metals from the soil may be absorbed by the rice plants which accumulate in the grains, and pose major health concerns after consumption (Wei et al., 2023). Numerous health problems such as renal damage, neurological abnormalities and an elevated risk of cancer, may result since prolonged exposure to heavy metals (Yang et al., 2021). Biochar obtained the specific surface area and porous structure that provides the ample site for heavy metal adherence (Liang et al., 2021). Adsorption occurs through different physical and chemical interactions which allows biochar to capture and retention of the toxic heavy metals over the biochar surface. As a consequence, there are less bioavailable heavy metals in the soil solution which limits the plant uptake (Mukherjee et al., 2023). Moreover, biochar has an ability to combine heavy metal ions to make fusion complexes to effectively decrease the mobility and bioavailability. Heavy metals may bind with the carboxyl, hydroxyl, and phenolic functional groups on the surface of biochar to create stable complexes that further immobilize the metals in the soil (Kim et al., 2015). Biochar can influence on the solubility of heavy metals in the soil which leads to precipitation reactions which convert soluble metal ions into insoluble forms. This process efficiently reduces the concentration of heavy metals available for plant uptake.

7. Long term effects of biochar application

Many researchers have reported the positive effects of the application of biochar to agricultural systems particularly in rice cultivation (Ahmad Bhat et al., 2022). The stability and consistency of biochar in paddy soil is one of its major characteristics. Compared to other organic materials, carbon is the main component of biochar which is extremely resistant to degradation (Bo et al., 2023). Due to this property, biochar can stay in the soil for decades or even centuries, improving the fertility and health of paddy soil (Ahmad Bhat et al., 2022). The half-life of biochar can vary from 100 to more than 1,000 years depending on the number of variables, including the type of feedstock, the production process, and the adjacent environment (Xie et al., 2015; Idbella et al., 2024). When applied regularly over time, biochar has improved the soil structure, aeration, and water retention, which in turn benefits rice crop growth and root development (Lehmann et al., 2015). Additionally, biochar provides the habitat for beneficial soil microbes which fostered the diverse microbial community which was essential for the nutrient cycling process. The long-term enhancement of soil fertility was further supported by biochar and its stable ability to absorb and retain key nutrients such as potassium, phosphate, and nitrogen (Ndor et al., 2016; Cheng et al., 2020; Haque et al., 2022). By reducing nutrient leaching and increasing nutrient availability, biochar promotes the sustainable crop improvement and decreases the reliance on synthetic fertilizers (Ding et al., 2022). It was essential to inspect the biochar influences on the structure and function of the microbial communities in the paddy soils over the long term. The associations among crop nutrient absorption, soil nutrients, and biochar remain poorly percept over extended periods. While the application of biochar in paddy cultivation has been reported to offer agronomic advantages by increasing soil carbon sequestration, it also effectively sequesters atmospheric carbon and helps mitigate climate change, as its stable carbon form can persist in the soil for decades (Spokas et al., 2012). This understanding is necessary to optimize the biochar application strategies in rice cultivation.

8. Economic and social considerations with biochar in paddy cultivation

The application of biochar in rice farming sector exists the unique opportunity to combine with economic and environmental sustainability (Jagnade et al., 2022). Biochar assists as the soil amendment that enhances nutrient preservation, crop yield improvement, and overall soil health and all crucial characteristics of sustainable farming practices. Successful integration of biochar into rice growing systems would be important to consider the economy of its production and use, as well as the social implications towards the farmers' predominantly in developing countries (Mohammadi et al., 2020). Implementation of biochar in rice farming sector has present the unique connection of environmental and economic sustainability (Ayaz et al., 2021). As a soil amendment, biochar has the grate potential to enhance the soil health, increases of crop yields, and improved nutrient retention, all those factors are critical in sustainable rice practices. The production cost depending on the nature of the feedstock, pyrolysis technology, and local labor and energy prices, has a significant impact on the economic sustainability of the biochar. The initial expenditure of pyrolysis equipment and production operating expenses may have to bear by farmer (Bach et al., 2016; Ayaz et al., 2021). Small scale production technologies and lowering the prices impacted to increase the access to biochar production and application in own farmlands. Production of biochar depends on the obtainability of suitable feed stocks. By-products such as rice husks are often underutilized in rice producing countries; it can be a freely available source for the synthesis of biochar. Integration of biochar manufacturing with existing agricultural practices can make the circular economy where waste materials are adapted into valuable soil amendments thus reduce the waste and enhance the sustainability (Mohammadi et al., 2020; Ayaz et al., 2021). Significant economic advantages of biochar application are the potential increase in crop yields and soil health improvement. Improved productivity can convert to profitability for farmers that making the initial investment in biochar production more attractive (Mohammadi et al., 2020).

Adoption of biochar in rice cultivation may lead to better livelihoods of farmers, predominantly in the developing countries where rice is the staple food and a primary source of income. Enhanced yields and reduced dependence on chemical fertilizers may have resulted in higher profits for farmers (Bagheri Novair et al., 2023). Through minimizing the input costs and increasing productivity, biochar may contribute to food security and economic stability of rural communities. Implementing of biochar production process and application serves as a substance for capacity building among farmers to enhance the productivity with improving the environmental health (Xie et al., 2015). Encouraging the production and use of biochar in rice-based farming systems needs effective strategies and encouragements through incentives. Governments and social groups can be able to encourage the use of biochar through offering the grants for research and development, financial incentives, and subsidies (Pourhashem et al., 2019). Moreover, strategies and guidelines have encouraged sustainable agricultural practices which can make the favorable environment for biochar production. To maximize biochar production methods, investigate the efficacy of various feedstocks, and evaluate the long-term effects on rice crop yields and soil health. Modified rice husk pyrolyzer was introduced by the Department of Agriculture, Sri Lanka concerning produce the more consistent and quality biochar product than the Kunthaniya. It had estimated that un-carbonized and incompletely carbonized portions and the ash portion in the output of Kunthaniya was nearly 11 and 10% even though both pyrolyzers were able to produce similar quantities of biochar

(Munasinghe et al. 2018). This modified rice husk pyrolizer can be used as cost effective and high-quality biochar production in the paddy farming sector.

9. Future research directions

The use of biochar in rice cultivation system is expected to improve soil health, enhance climate resilience, and support sustainability in the future. In order to increase rice yield output and resource efficiency, efforts are increasingly focused on optimizing biochar types and application techniques suited to specific soil and climatic surroundings (Lehmann et al., 2015). Combining biochar with both organic and inorganic fertilizers is expected to reduce contamination, improve nutrient use efficiencies and lower fertilizer requirements in the rice farming sector. Technological expansions in biochar engineering, including microbe inoculated or nutrient enriched biochar formulation may support the potential enhancement of plant health and soil microbial activity in the agroecosystem (Yin et al., 2021). Application of biochar may also contribute to climate change mitigation by reducing emissions of CH_4 and CO_2 (Singh et al., 2017). Furthermore, biochar can enhance the structure of the soil and retention of soil water which is especially important in paddy farming systems affected by unpredictable rainfall and water scarcity. Additionally, converting rice residues into biochar helps reduce agricultural waste and promotes energy efficiency in global circular agriculture systems (Khater et al., 2024).

10. Conclusions

The substantial potential of biochar as a viable soil amendment to increase rice crop productivity and address urgent environmental problems has been emphasized in this review. In rice cultivation system, the application of biochar proved in improving the physical and chemical properties of the soil, nutrient retention, acidity and cation exchanging ability, water holding capacity, bulk density which led to improved crop performance and productivity. Furthermore, biochar assists as a valuable material for mitigating GHG emissions, immobilizing heavy metals and encouraging soil health through improved microbial activity and community which increase the organic matter dynamics. The incorporation of biochar into rice-based farming not only offers economic assistance through reducing the fertilizer inputs and increased productivity but also promotes the social benefits through improving livelihoods and increasing food security mainly in the developing countries where rice is the staple food crop. Understanding of the behavior of different feedstock materials, manufacture procedures, and pyrolysis conditions influenced on biochar's characteristics may enable tailored applications which maximize the benefits of assorted agricultural settings. More research and development should focus on the most effective application methods with proper time and rates of biochar in rice ecosystems.

References

Abeysekara, I. and Rathnayake, I. (2024). Global Trends in Rice Production, Consumption and Trade. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4948477

Abrishamkesh, S., Gorji, M., Asadi, H., Bagheri-Marandi, G. H. and Pourbabaee, A. A. (2015). Effects of rice husk biochar application on the properties of alkaline soil and lentil growth. Soil and Tillage Research, 145, 22-28. https://doi.org/10.1016/j.still.2014.08.002.

Abukari, A., Abunyewa, A. A. and Issifu, H. (2018). Effect of rice husk biochar on nitrogen uptake and grain yield of maize in the Guinea savanna zone of Ghana. UDS International Journal of Development 5(2), 1-6. DOI: http://www.udsijd.org.

Adebajo, S. O., Oluwatobi, F., Akintokun, P. O., Ojo, A. E., Akintokun, A. K. and Gbodope, I. S. (2022). Impacts of rice-husk biochar on soil microbial biomass and agronomic performances of tomato (*Solanum lycopersicum* L.). Environmental Science and Pollution Research, 29(17), 24762-24775. https://doi.org/10.1007/s11356-021-17809-8.

AgStat. (2016). The pocket book of agriculture statistics, Socio Economic and Planning Centre, Department of Agriculture, Peradeniya, Sri Lanka.

Ahmad Bhat, S., Kuriqi, A., Dar, M. U. D., Bhat, O., Sammen, S. Sh., Towfiqul Islam, A. R. Md., Elbeltagi, A., Shah, O., AI-Ansari, N., Ali, R. and Heddam, S. (2022). Application of Biochar for Improving Physical, Chemical, and Hydrological Soil Properties: A Systematic Review. *Sustainability*, *14*(17), 11104. https://doi.org/10.3390/su141711104.

Ali, I., Ullah, S., He, L., Zhao, Q., Iqbal, A., Wei, S., Shah, T., Ali, N., Bo, Y., Adnan, M., Amanullah, and Jiang, L. (2020). Combined application of biochar and nitrogen fertilizer improves rice yield, microbial activity and N-metabolism in a pot experiment. PeerJ, 8, e10311. https://doi.org/10.7717/peerj.10311.

Ali, I., Zhao, Q., Wu, K., Ullah, S., Iqbal, A., Liang, H., Zhang, J., Amanullah, J. M., Khan, A., Khan, A. A. and Jiang, L. (2021). Biochar in combination with nitrogen fertilizer is a technique to enhance physiological and morphological traits of rice (*Oryza sativa* L.) by improving soil physio-biochemical properties. Journal of Plant Growth Regulation 41, 2406-2420. DOI: https://doi.org/10.1007/s00344-021-10454-8.

Ali, I., Yuan, P., Ullah, S., Iqbal, A., Zhao, Q., Liang, H., Khan, A. I., Hua, Z., Wu, X., Wei, S., Gu, M. and Jiang, L. (2022). Biochar amendment and nitrogen fertilizer contribute to the changes in soil properties and microbial communities in paddy field. Frontiers in Microbiology 13, 834751. DOI: https://doi.org/10.3389/fmicb.2022.834751.

Amalina, F., Razak, A. S. A., Krishnan, S., Sulaiman, H., Zularisam, A. W. and Nasrullah, M. (2022). Biochar production techniques utilizing biomass waste-derived materials and environmental applications - A review. Journal of Hazardous Materials Advances, 7, 100134. https://doi.org/10.1016/j.hazadv.2022.100134.

Armynah, B., Atika, Djafar, Z., Piarah, W. H. and Tahir, D. (2018). Analysis of Chemical and Physical Properties of Biochar from Rice Husk Biomass. Journal of Physics: Conference Series, 979, 012038. https://doi.org/10.1088/1742-6596/979/1/012038.

Ayaz, M., Feizienė, D., Tilvikienė, V., Akhtar, K., Stulpinaitė, U. and Iqbal, R. (2021). Biochar Role in the Sustainability of Agriculture and Environment. Sustainability, 13(3), 1330. https://doi.org/10.3390/su13031330.

Asadi, H., Ghorbani, M., Rezaei-Rashti, M., Abrishamkesh, S., Amirahmadi, E., Chengrong, C. and Gorji, M. (2021). Application of Rice Husk Biochar for Achieving Sustainable Agriculture and Environment. Rice Science, 28 (4), 325 - 343. https://doi.org/10.1016/j.rsci.2021.05.004.

Babiker, S., Id, D., Mukhtar, H. and Shaharun, M.S. (2020). Preparation and Characterization of Rice Husk Adsorbents for Phenol Removal from Aqueous Systems. Plos one. doi: 10.1371/journal.

Bach, M., Wilske, B. and Breuer, L. (2016). Current economic obstacles to biochar use in agriculture and climate change mitigation. Carbon Management, 7(3 - 4), 183 - 190. https://doi.org/10.1080/17583004.2016.1213608.

Bagheri Novair, S., Cheraghi, M., Faramarzi, F., Asgari Lajayer, B., Senapathi, V., Astatkie, T. and Price, G. W. (2023). Reviewing the role of biochar in paddy soils: An agricultural and environmental perspective. Ecotoxicology and Environmental Safety, 263, 115228. https://doi.org/10.1016/j.ecoenv.2023.115228.

Barman, K. and Kandpal, G. (2019). Impact of rice husk biochar on agriculture. Bulletin of Environment Pharmacology and Life Sciences 8(2), 25-27. DOI: https://bepls.com/bepls-jan2019/5.pdf.

Bi, Y., Kuzyakov, Y., Cai, S. and Zhao, X. (2021). Accumulation of organic compounds in paddy soils after biochar application is controlled by iron hydroxides. Science of the Total Environment, 764, 144300. https://doi.org/10.1016/j.scitotenv.2020.144300.

Bo, X., Zhang, Z., Wang, J., Guo, S., Li, Z., Lin, H., Huang, Y., Han, Z., Kuzyakov, Y. and Zou, J. (2023). Benefits and limitations of biochar for climate-smart agriculture: A review and case study from China. Biochar, 5(1), 77. https://doi.org/10.1007/s42773-023-00279-x.

Bolan, S., Hou, D., Wang, L., Hale, L., Egamberdieva, D., Tammeorg, P., Li, R., Wang, B., Xu, J., Wang, T., Sun, H., Padhye, L. P., Wang, H., Siddique, K. H. M., Rinklebe, J., Kirkham, M. B. and Bolan, N. (2023). The potential of biochar as a microbial carrier for agricultural and environmental applications. Science of the Total Environment, https://doi.org/10.1016/j.scitotenv.2023.163968.

Brahima, T., Fasse, S., Amadoun, B. and Min, H. (2017). Effects of different fertilizers on methane emission from paddy field of Zhejiang, China. African Journal of Environmental Science and Technology, 11(1), 89-93. https://doi.org/10.5897/AJEST2016.2189.

Brown, A.E., Adams, J.M.M., Grasham, O.R., Camargo-Valero, M.A. and Ross, A.B. (2020). An assessment of different integration strategies of hydrothermal carbonisation and anaerobic digestion of water hyacinth. Energies, 13 (22), 5983. doi: 10.3390/en13225983.

Butnan, S. and Vityakon, P. (2023). Lengths of time of rice husk biochar incorporation before planting affect soil properties and rice yield. Agronomy 13(6), 1445. DOI: https://doi.org/10.3390/agronomy1306144515.

Cheng, S., Chen, T., Xu, W., Huang, J., Jiang, S. and Yan, B. (2020). Application Research of Biochar for the Remediation of Soil Heavy Metals Contamination: A Review. Molecules, 25(14), 3167. https://doi.org/10.3390/molecules25143167.

Clough, T. J., Condron, L. M., Kammann, C. and Muller, C. (2013). A review of biochar and soil nitrogen dynamics. Agronomy 3(2), 275-293. DOI: https://doi.org/10.3390/agronomy3020275.

Daful, A.G. and Chandraratne, M.R. (2018). Biochar production from biomass waste-derived material. Encyclopedia of Renewable and Sustainable Materials, doi: 10.1016/B978-0-12-803581-8.11249-4.

Dhamira, A. and Aminda, F. R. (2023). Rice Production Risk in Main Producing Countries 1961-2021. Buletin Penelitian Sosial Ekonomi Pertanian Fakultas Pertanian Universitas Haluoleo, 25(2), 143–150. https://doi.org/10.37149/bpsosek.v25i2.921.

Ding, Y., Zhu, S., Pan, R., Bu, J., Liu, Y. and Ding, A. (2022). Effects of Rice Husk Biochar on Nitrogen Leaching from Vegetable Soils by 15N Tracing Approach. Water, 14(21), 3563. https://doi.org/10.3390/w14213563.

Dissanayake, D. K. R. P. L., Dharmakeerthi, R. S., Karunarathna, A. K. and Dandeniya, W. S. (2018). Changes in structural and chemical properties of rice husk biochar co-pyrolysed with Eppawala rock phosphate under different temperatures. Tropical Agricultural Research, 30(1), 19. https://doi.org/10.4038/tar.v30i1.8275.

Gong, D., Xu, X., Wu, L., Dai, G., Zheng, W. and Xu, Z. (2020). Effect of biochar on rice starch properties and starch-related gene expression and enzyme activities. Sci Rep 10:16917

Gowthami, V. S. S., Venkateswarlu, B., Prasad, P. V. N., Sujani, R. C., Kumari, S. R. and Naga, J. C. (2022). Effect of rice husk biochar and inorganic nitrogen on growth and yield parameters of direct seeded rice. The Andhra Agriculture Journal 69(2), 179–187. DOI: 69-2-004.pdf.

Hamad, H. N. and Idrus, S. (2022). Recent Developments in the Application of Bio-Waste-Derived Adsorbents for the Removal of Methylene Blue from Wastewater: A Review. Polymers. 14(783), 2-39. . https://doi.org/10.3390/polym14040783.

Haque, A. N. A., Uddin, Md. K., Sulaiman, M. F., Amin, A. M., Hossain, M., Solaiman, Z. M., Aziz, A. A. and Mosharrof, M. (2022). Combined Use of Biochar with 15Nitrogen Labelled Urea Increases Rice Yield, N Use Efficiency and Fertilizer N Recovery under Water-Saving Irrigation. Sustainability, 14(13), 7622. https://doi.org/10.3390/su14137622.

Hashim, N., Ali, M. M., Mahadi, M. R., Abdullah, A. F., Wayayok, A., Mohd Kassim, M. S. and Jamaluddin, A. (2024). Smart Farming for Sustainable Rice Production: An Insight into Application, Challenge, and Future Prospect. Rice Science, 31(1), 47-61. https://doi.org/10.1016/j.rsci.2023.08.004.

Hidayat, Rahmat, A., Nissa, R. C., Sukamto, Nuraini, L., Nurtanto, M. and Ramadhani, W. S. (2023). Analysis of rice husk biochar characteristics under different pyrolysis temperature. IOP Conference Series: Earth and Environmental Science, 1201(1), 012095. https://doi.org/10.1088/1755-1315/1201/1/012095.

Hoang, T. T. H., Truong, T. D. H., Tran, T. D. and Tran, T. H. S. (2024). Management of heavy metals in rice (*Oryza sativa*) soils by silicon rich biochar materials. The Indian Journal of Agricultural Sciences, 94(3), 241-245. https://doi.org/10.56093/ijas.v94i3.142653.

Idbella, M., Baronti, S., Giagnoni, L., Renella, G., Becagli, M., Cardelli, R., Maienza, A., Vaccari, F. P. and Bonanomi, G. (2024). Long-term effects of biochar on soil chemistry, biochemistry, and microbiota: Results from a 10-year field vineyard experiment. Applied Soil Ecology, 195, 105217. https://doi.org/10.1016/j.apsoil.2023.105217.

Jaafar, N. M., Clode, P. L. and Abbott, L. K. (2015). Biochar-Soil Interactions in Four Agricultural Soils. Pedosphere, 25(5), 729-736. https://doi.org/10.1016/S1002-0160(15)30054-0.

Jagnade, P., Panwar, N. L., Gupta, T. and Agrawal, C. (2022). Role of Biochar in Agriculture to Enhance Crop Productivity: An Overview. Bio interference in applied chemistry. Volume 13, Issue 5, 2023, 429. https://doi.org/10.33263/BRIAC135.429.

Karam, D. S., Nagabovanalli, P., Rajoo, K. S., Ishak, C. F., Abdu, A., Roshli, Z., Muharam, F. M. and Zulperi, D. (2022). An overview on the preparation of rice husk biochar, factors affecting its properties, and its agricultural applications. Journal of the Saudi Society of Agricultural Sciences 21(1), 149-159. DOI: https://doi.org/10.1016/j.jssas.2021.09.002.

Khater, E.S., Bahnasawy, A., Hamouda, R., Sabahy, A., Abbas, W. and Morsy, O. M. (2024). Biochar production under different pyrolysis temperatures with different types of agricultural wastes. Scientific Reports, 14(1), 2625. https://doi.org/10.1038/s41598-024-52336-5.

Kim, H.S., Kim, K.R., Kim, H.J., Yoon, J.H., Yang, J. E., Ok, Y. S., Owens, G. and Kim, K.H. (2015). Effect of biochar on heavy metal immobilization and uptake by lettuce (*Lactuca sativa* L.) in agricultural soil. Environmental Earth Sciences, 74(2), 1249 - 1259. https://doi.org/10.1007/s12665-015-4116-1.

Lai, L., Ismail, M. R., Muharam, F. M., Yusof, M. M., Ismail, R. and Jaafar, N. M. (2017). Effects of Rice Straw Biochar and Nitrogen Fertilizer on Rice Growth and Yield. Asian Journal of Crop Science, 9(4), 159-166. https://doi.org/10.3923/ajcs.2017.159.166.

Lachke, A. (2002). Biofuel from D-xylose the Second Most Abundant Sugar http://www. iisc.ernet.in/academy/resonance/May20 02/pdf/May2002p50-58.pdf

Lehmann, J. and Joseph, S. (2009). Biochar for Environmental Management: Science and Technology. Earthscan. ISBN: 978-1-84407-658-1.

Lehmann, J., Kuzyakov, Y., Pan, G. and Ok, Y. S. (2015). Biochars and the plant-soil interface. Plant and Soil, 395(1-2), 1-5. https://doi.org/10.1007/s11104-015-2658-3.

Liang, F., Li, G., Lin, Q. and Zhao, X. (2014). Crop Yield and Soil Properties in the First 3 Years After Biochar Application to a Calcareous Soil. Journal of Integrative Agriculture, 13(3), 525–532. https://doi.org/10.1016/S2095-3119(13)60708-X.

Liang, M., Lu, L., He, H., Li, J., Zhu, Z. and Zhu, Y. (2021). Applications of Biochar and Modified Biochar in Heavy Metal Contaminated Soil: A Descriptive Review. Sustainability, 13(24), 14041. https://doi.org/10.3390/su132414041.

Liu, S. W., Zhang, Y. J., Zong, Y. J., Hu, Z. Q., Wu, S., Zhou, J., Jin, Y. G. and Zou, J. W. (2016). Response of soil carbon dioxide fluxes, soil organic carbon, and microbial biomass carbon to biochar amendment: A meta-analysis. GCB Bioenergy 8, 392-406. DOI: https://doi.org/10.1111/gcbb.12265.

Liu, Q., Wu, C., Wei, L., Wang, S., Deng, Y., Ling, W., Xiang, W., Kuzyakov, Y., Zhu, Z. and Ge, T. (2024). Microbial mechanisms of organic matter mineralization induced by straw in biochar-amended paddy soil. Biochar, 6(1), 18. https://doi.org/10.1007/s42773-024-00312-7.

Luo, D., Meng, X., Zheng, N., Li, Y., Yao, H. and Chapman, S. J. (2021). The anaerobic oxidation of methane in paddy soil by ferric iron and nitrate, and the microbial communities involved. Science of The Total Environment, 788, 147773. https://doi.org/10.1016/j.scitotenv.2021.147773.

Mboyerwa, P. A., Kibret, K., Mtakwa, P. and Aschalew, A. (2022). Greenhouse gas emissions in irrigated paddy rice as influenced by crop management practices and nitrogen fertilization rates in eastern Tanzania. Frontiers in Sustainable Food Systems, 6, 868479. https://doi.org/10.3389/fsufs.2022.868479.

Mikhaylov, A., Moiseev, N., Aleshin, K. and Burkhardt, T. (2020). Global climate change and greenhouse effect. Entrepreneurship and Sustainability Issues, 7(4), 2897 - 2913. https://doi.org/10.9770/jesi.2020.7.4.

Mohammadi, A., Khoshnevisan, B., Venkatesh, G. and Eskandari, S. (2020). A Critical Review on Advancement and Challenges of Biochar Application in Paddy Fields: Environmental and Life Cycle Cost Analysis. Processes, 8(10), 1275. https://doi.org/10.3390/pr8101275.

Mukherjee, S., Singh, S. K., Jatav, S. S., Patra, A. and Reddy, G. P. (2023). Effect of Biochar Application on Heavy Metal accumulation in Different Parts of Paddy Plant. International Journal of Environment and Climate Change, 13(11), 4491-4500. https://doi.org/10.9734/ijecc/2023/v13i113629.

Munasinghe, S.T., Dharmakeerthi, R.S., Weerasinghe, P. and Madusanka, L.G.S. (2018). preparation of biochar as a soil amendment from rice husk and corn cob by slow pyrolysis process. Vol.166 (2).

Ndor, E., Jayeoba, J. O., Asadu, C. L. A. and Iheshiulo, E. M. A. (2016). Growth, Nutrient Uptake and Dry Matter Yield of Maize (*Zea Mays* L) Grown in Soil Amended with Rice Husk and Sawdust Biochar. International Journal of Scientific Research in Agricultural Sciences, 3(3), 99-103. https://doi.org/10.12983/ijsras-2016-p0099-0103.

Ning, C., Liu, R., Kuang, X., Chen, H., Tian, J. and Cai, K. (2022). Nitrogen Fertilizer Reduction Combined with Biochar Application Maintain the Yield and Nitrogen Supply of Rice but Improve the Nitrogen Use Efficiency. Agronomy, 12(12), 3039. https://doi.org/10.3390/agronomy12123039.

Novak, J. M., Sigua, G. C., Ducey, T. F., Watts, D. W. and Stone, K. C. (2019). Designer Biochars Impact on Corn Grain Yields, Biomass Production, and Fertility Properties of a Highly-Weathered Ultisol. Environments. 6(64), 2-15. doi:10.3390/environments6060064.

Oladele, S. O., Adeyemo, A. J. and Awodun, M. A. (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.

Oo, A. Z., Sudo, S., Akiyama, H., Win, K. T., Shibata, A., Yamamoto, A., Sano, T. and Hirono, Y. (2018). Effect of dolomite and biochar addition on N_2O and CO_2 emissions from acidic tea field soil. Plos One, 13(2). https://doi.org/10.1371/journal.pone.0192235.

Pahnila, M., Koskela, A., Sulasalmi, P. and Fabritius, T. (2023). A Review of Pyrolysis Technologies and the Effect of Process Parameters on Biocarbon Properties. Energies, 16(19), 6936. https://doi.org/10.3390/en16196936.

Pourhashem, G., Hung, S. Y., Medlock, K. B. and Masiello, C. A. (2019). Policy support for biochar: Review and recommendations. GCB Bioenergy, 11(2), 364 - 380. https://doi.org/10.1111/gcbb.12582.

Qayyum, M.F., Haider, G., Raza, M.A., Mohamed, A.K.S.H., Rizwan, M., El-Sheikh, M.A. and Ali, S. (2020). Straw-based biochar mediated potassium availability and increased growth and yield of cotton (*Gossypium hirsutum* L.). J. Saudi Chem. Soc. 24 (12), 963 - 973. doi: 10.1016/J.JSCS.2020.10.004 .

Qian, L., Chen, L., Joseph, S., Pan, G., Li, L., Zheng, J., Zhang, X., Zheng, J., Yu, X. and Wang, J. (2014). Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China. Carbon Management, 5(2), 145 - 154. https://doi.org/10.1080/17583004.2014.912866.

Rawat, J., Saxena, J. and Sanwal, P. (2019). Biochar: A Sustainable Approach for Improving Plant Growth and Soil Properties. An Imperative Amendment for Soil and the Environment. Intech Open. https://doi.org/10.5772/intechopen.82151.

Saarnio, S., Heimonen, K. and Kettunen, R. (2013). Biochar addition indirectly affects N_2O emissions via soil moisture and plant N uptake. Soil Biology and Biochemistry, 58, 99 - 106. https://doi.org/10.1016/j.soilbio.2012.10.035.

Selvarajh, G., Ch'ng, H. Y., Md Zain, N., Seong Wei, L., Liew, J. Y., Mohammad Azmin, S. N. H., Naher, L., Abdullah, P. S., Ahmed, O. H., Jalloh, M. B. and Damrongrak, I. (2024). Enriched rice husk biochar superior to commercial biochar in ameliorating ammonia loss from urea fertilizer and improving plant uptake. Heliyon, 10(11). https://doi.org/10.1016/j.heliyon.2024.

Shahbaz, M., Nouss, A., Parthasarathy, P., Abdelaal, A.H., Mackey, H., McKay, G. and Al Ansari, T. (2020). Investigation of biomass components on the slow pyrolysis products yield using Aspen Plus for techno-economic analysis. Biomass Convers. Biorefinery doi: 10.1007/s13399-020-01040-1.

Singh, A.K. and Chandra, R., (2019). Pollutants released from the pulp paper industry: aquatic toxicity and their health hazards. *Aquat. Toxicol.* 211, 202-216. doi: 10.1016/j.aquatox.2019.04.007.

Singh, C., Tiwari, S., Boudh, S. and Singh, J. S. (2017). Biochar Application in Management of Paddy Crop Production and Methane Mitigation, Agro-Environmental Sustainability Springer International Publishing. https://doi.org/10.1007/978-3-319-49727-3-7.

Singh, C., Tiwari, S., Gupta, V. K. and Singh, J. S. (2018). The effect of rice husk biochar on soil nutrient status, microbial biomass and paddy productivity of nutrient poor agriculture soils. CATENA, 171, 485-493. https://doi.org/10.1016/j.catena.2018.07.042.

Spokas, K. A., Cantrell, K. B., Novak, J. M., Archer, D. W., Ippolito, J. A., Collins, H. P., Boateng, A. A., Lima, I. M., Lamb, M. C., McAloon, A. J., Lentz, R. D. and Nichols, K. A. (2012). Biochar: A Synthesis of Its Agronomic Impact beyond Carbon Sequestration. Journal of Environmental Quality, 41, 973-989.

Srivastava, P., Gadi, Y., Supriya, Bhojendra, Lytand, W., Singh, B. V. and Katiyar, D. (2023). Biochar's Influence on Soil Microorganisms: Understanding the Impacts and Mechanisms. International Journal of Plant & Soil Science, 35(18), 455 - 464. https://doi.org/10.9734/ijpss/2023/v35i183310.

Tan, T., Xu, Y., Liao, X., Yi, Z. and Xue, S. (2024). Formulating new types of rice husk biochar-based fertilizers for the simultaneous slow-release of nutrients and immobilization of cadmium. GCB Bioenergy, 16(6), e13142. https://doi.org/10.1111/gcbb.13142.

Thomas, S. C. and Gale, N. (2015). Biochar and forest restoration: A review and meta-analysis of tree growth responses. New Forests, 46(5-6), 931-946. https://doi.org/10.1007/s11056-015-9491-7.

Thomas, P., Lai, C.W., Rafie, M. and Johan, B. (2019). Journal of Analytical and Applied Pyrolysis Recent developments in biomass-derived carbon as a potential sustainable mate-rial for super-capacitor-based energy storage and environmental applications. The Journal of Analytical and Applied Pyrolysis, 140, 54-85. doi: 10.1016/j.jaap.2019.03.021.

Tsai, C. C. and Chang, Y. F. (2021). Higher Biochar Rate Can Be Efficient in Reducing Nitrogen Mineralization and Nitrification in the Excessive Compost-Fertilized Soils. Agronomy, 11(4), 617. https://doi.org/10.3390/agronomy11040617.

Ullah, Z., Akmal, M. S., Ahmed, M., Ali, M., Khan, A. Z. and Ziad, T. (2018). Effect of Biochar on Maize Yield and Yield Components in Rainfed Conditions. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3583644.

Verheijen, F., Jeffery, S., Bastos, A. C., van der Velde, M. and Diafas, I. (2010). Biochar application to soils: A critical scientific review of effects on soil properties, processes, and functions. European Commission, Joint Research Centre. https://publications.jrc.ec.europa.eu/repository/handle/JRC55799.

Wei, R., Chen, C., Kou, M., Liu, Z., Wang, Z., Cai, J. and Tan, W. (2023). Heavy metal concentrations in rice that meet safety standards can still pose a risk to human health. Communications Earth & Environment, 4(1), 84. https://doi.org/10.1038/s43247-023-00723-7.

Williams, R., Belo, J. B., Lidia, J., Soares, S., Ribeiro, D., Moreira, C. L., Almeida, L., Barton, L. and Erskine, W. (2023). Productivity gains in vegetables from rice husk biochar application in nutrient-poor soils in Timor-Leste. Scientific Reports 13, 10858. DOI: https://doi.org/10.1038/s41598-023-38072-2.

Xiang, Y., Deng, Q., Duan, H. and Guo, Y. (2017). Effects of biochar application on root traits: A meta-analysis. GCB Bioenergy, 9(10), 1563-1572. https://doi.org/10.1111/gcbb.12449.

Xie, T., Reddy, K. R., Wang, C., Yargicoglu, E. and Spokas, K. (2015). Characteristics and Applications of Biochar for Environmental Remediation: A Review. Critical Reviews in Environmental Science and Technology, 45(9), 939-969. https://doi.org/10.1080/10643389.2014.924180.

Xu, Q., Wang, J., Liu, Q., Chen, Z., Jin, P., Du, J., Fan, J., Yin, W., Xie, Z. and Wang, X. (2022). Long-Term Field Biochar Application for Rice Production: Effects on Soil Nutrient Supply, Carbon Sequestration, Crop Yield and Grain Minerals. Agronomy, 12(8), 1924. https://doi.org/10.3390/agronomy12081924.

Yaligar, R., Balakrishnan, P., Satishkumar, U., Kanannavar, P. S., Halepyati, A. S., Jat, M. L. and Rajesh, N. L. (2017). Water requirement of Paddy under Different Land Levelling, Cultivation Practices and Irrigation Methods. International Journal of Current Microbiology and Applied Sciences, 6(9), 3790-3796. https://doi.org/10.20546/ijcmas.2017.609.468.

Yin, X., Peñuelas, J., Xu, X., Sardans, J., Fang, Y., Wiesmeier, M., Chen, Y., Chen, X. and Wang, W. (2021). Effects of addition of nitrogen-enriched biochar on bacteria and fungi community structure and C, N, P, and Fe stoichiometry in subtropical paddy soils. European Journal of Soil Biology, 106, 103351. https://doi.org/10.1016/j.ejsobi.2021.103351.

Zavalloni, C., Alberti, G., Biasiol, S., Vedove, G. D., Fornasier, F., Liu, J. and Peressotti, A. (2011). Microbial mineralization of biochar and wheat straw mixture in soil: A short-term study. Applied Soil Ecology, 50, 45–51. https://doi.org/10.1016/j.apsoil.2011.07.012.

Zhang, H., Cheng, Y., Zhong, Y., Ni, J., Wei, R. and Chen, W. (2024). Roles of biochars' properties in their water-holding capacity and bound water evaporation: Quantitative importance and controlling mechanism. Biochar, 6(1), 30. https://doi.org/10.1007/s42773-024-00317-2.

Zhao, Y., Jiang, H., Gao, J., Feng, Y., Yan, B., Li, K., Lan, Y. and Zhang, W. (2023). Effects of nitrogen co-application by different biochar materials on rice production potential and greenhouse gas emissions in paddy fields in northern China. Environmental Technology & Innovation, 32, 103242. https://doi.org/10.1016/j.eti.2023.103242.