Biochar Implementation in Rice Paddies for Addressing Greenhouse Gas Emissions and Nutrient Loss : A Review

Abstract

Eco-challenges like greenhouse gas (GHG) emissions and nutrient depletion are key threats to the health of rice field ecosystems. Biochars (BCs) - porous, carbon-dense materials with substantial surface areas and an abundance of surface functional groups - are emerging as a viable solution for these issues, offering a way to increase rice production and address environmental concerns. Despite this potential, there is still a need for a comprehensive understanding of BCs' performance characteristics and their environmental interactions with rice paddy soils. The beneficial outcomes of using BCs, including enhanced rice growth and yield, decreased nutrient loss, and reduced GHG emissions. Factors like biomass type, pyrolysis temperature, and modification process significantly influence BCs' performance. The use of BCs can boost rice production while mitigating emissions of CO_2, N_2O, and CH_4. They do this by improving soil properties, encouraging microbial diversity, supplying nutrients, and minimizing nutrient losses. However, the potential ecological hazards related to the use of BCs in rice paddies. These hazards include inconsistent research outcomes and the possibility of secondary pollution. Future research must address these challenges to ensure the sustainable application of BCs.

Key word: Biochar Implementation , Greenhouse Gas , maize yield , nitrogen cycle

Introduction

Biochar, a carbon-rich material produced from the pyrolysis of biomass, holds significant potential for addressing pressing environmental concerns in the agricultural sector (Lehmann & Joseph, 2015). Biochar's unique properties, such as its high porosity, stability, and nutrient-retention capacity, make it an attractive amendment for soil remediation and greenhouse gas (GHG) mitigation strategies (Lehmann & Joseph, 2015). Greenhouse gases, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are major contributors to global warming and climate change (IPCC, 2014). In agriculture, these gases are primarily emitted during the decomposition of organic materials and the use of synthetic fertilizers (IPCC, 2014). Rice paddies, in particular, are significant emitters of CH_4 due to the anaerobic conditions that prevail during the flooded periods of the rice cultivation cycle (Sass *et al.*, 1992). Nutrient loss, another critical concern in agriculture, occurs when essential nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), are lost from the soil, reducing soil fertility and crop productivity (Galloway *et al.*, 2008). The mechanisms for nutrient loss include leaching, runoff, volatilization, and erosion, and they are often exacerbated by inappropriate fertilizer application and other poor management practices (Galloway *et al.*, 2008). In rice paddies, nutrient loss can result in substantial yield reductions, negatively impacting food security and farmers' livelihoods (Dobermann *et al.*, 2004). The advent of biochar offers an innovative approach to addressing these challenges. Theoretically, biochar's porous structure can capture and store GHGs, particularly CO_2, thus reducing their emissions into the atmosphere (Woolf *et al*., 2010).

Biochar is gaining significant attention due to its potential for carbon (C) sequestration, improvement of soil health, fertility enhancement, and crop productivity and quality [Alkharabsheh et al.2021; Siedt et al.2021]. Biochar can enhance nutrient retention in the soil by attracting and holding onto nutrient ions, thereby reducing nutrient leaching and enhancing soil fertility (Lehmann *et al*., 2003). In the context of rice paddies, biochar application might prove particularly beneficial given the sector's high GHG emissions and nutrient loss concerns (Haefele *et al*., 2011). Despite the potential of BCs as a cost-effective soil amendment, a comprehensive review of their performance characteristics and environmental behavior in paddy soils is still lacking. Different methods of preparing biochar and their application strategies can yield varying results in addressing specific challenges in rice paddies. Furthermore, there is limited information on the potential secondary risks associated with biochar application in rice fields. Therefore, there is a need to systematically summarize the effects of BCs with different performance characteristics on improving environmental issues in paddy fields, increasing rice yield, and assessing potential ecological risks.

The (Table 1) provides insightful data regarding the characteristics of various biochars produced from different feedstocks at varying pyrolysis temperatures. Biochar properties including pH, specific surface area (SSA), ash content, recalcitrant index (R50), atomic ratios (H/C, O/C), content of mineral elements (P, K, Ca, Mg) and cation exchange capacity (CEC) are reported, which are key indicators for biochar's potential applications especially in soil amendment and carbon sequestration. Pine sawdust biochar produced at increasing pyrolysis temperatures (350°C to 650°C) displayed an increase in pH, SSA and ash content with a corresponding decrease in the recalcitrant index and atomic ratio H/C (Lehmann & Joseph, 2015). The increasing ash content with pyrolysis temperature could be attributed to the increased mineral concentration at high temperatures, as organic constituents are largely vaporized (Zimmerman, 2010). The influence of pyrolysis temperature on biochar characteristics is also demonstrated with vine pruning, orange pomace, Conocarpus waste, and algal biomass. An increasing trend in pH and 7 decreasing trend in H/C ratio, recalcitrant index (R50) and cation exchange capacity (CEC) are observed with increasing pyrolysis temperature (Novak & Busscher, 2012). Biochars produced from sewage sludge at 500°C, 700°C and 900°C display high ash content which could be associated with the inorganic fraction in the original feedstock. Furthermore, the SSA and CEC both increased with the increase in temperature, indicating the enhancement of biochar's surface reactivity and nutrient retention capability (Ahmad *et al*., 2014). Biochar produced from modified feedstocks such as $FeCl_3$ and $AlCl_3$ modified rice straw, and poultry litter also showed distinct characteristics. The modifications in feedstock might alter the biochar's properties, enhancing their specific functionalities. For instance, $FeCl_3$ modification tends to improve the specific surface area and nutrient retention capacity of biochars (Song & Guo, 2012). It is worth noting that these properties will affect biochar's behavior in the environment, and its effectiveness in specific applications. For example, high pH biochars might be better applied in acidic soils, high SSA biochars might provide more sites for nutrient adsorption and hence more beneficial for nutrient-poor soils, while high ash content biochars might be more resilient to degradation, making them more suitable for carbon sequestration (Chen *et al*., 2008).

Table:1 Influence of feedstock type, pyrolysis temperature and on the characteristics of Biochars (BCs).

Feedstocks	**Temperature (°C)**	**pH**	**Specific Surface Area (SSA) ($m^2 g^{-1}$)**	**Ash (%)**	**Recalcitrant Index (R50)**	**Atomic Ratio (H/C, O/C)**	**Content of Mineral Elements (P, K, Ca, Mg) (a: g/kg; b: water-soluble g/kg)**	**Cation Exchange Capacity (CEC) (cmol kg^{-1})**
Pine sawdust	350	5.75	3.39	12.30	1.19	(0.44, 0.07) a		56.13
	450	6.31	179.77	15.60	0.87	(0.32, 0.08) a		52.43
	550	6.66	431.91	11.90	0.80	(0.26, 0.10) a		47.43
	650	6.84	443.79	21.70	0.66	(0.14, 0.10) a		39.22
Vine pruning	250	7.35	5.00	1.22	0.55	(0.06, 0.07) b	(0.03) b	60.95
	350	10.26	8.30	0.75	0.25	(0.07, 0.04) b	(0.02) b	47.38
	600	11.31	11.50	0.41	0.13	(0.11, 0.01) b	(0.01) b	32.23
Orange pomace	250	7.29	6.70	1.29	0.44	(0.03, 0.11) b	(0.03) b	52.57
	350	9.88	11.30	0.84	0.19	(0.06, 0.02) b	(0.01) b	35.23
	600	10.45	16.30	0.42	0.11	(0.10, 0.01) b	0 b	25.59
Conocarpus waste	200	7.37	4.53	0.06	0.41	(0.84, 0.38) a	(43.4) a	3.43
	400	9.67	5.27	0.04	0.18	(0.88, 0.54) a	(51.8) a	3.98

	600	12.21	8.56	0.02	0.08	(1.11, 0.90) a	(64.7) a	4.79
	800	12.38	8.64	0.01	0.06	(1.34, 1.15) a	(67.5) a	7.81
Algal biomass	250	8.72	22.90	1.21	0.71	(3.24, 0.75) b	(0.07) b	81.23
	350	12.98	33.40	0.86	0.33	(4.12, 0.22) b	(0.08) b	62.80
	600	13.66	42.70	0.38	0.15	(5.49, 0.16) b	(0.08) b	49.80
Tire	300	6.95	13.10	0.01 b	0.13	(0.63, 0.04) b		5.53
	500	8.94	10.30	0.03 b	0.49	(2.72, 0.10) b		51.90
	700	10.2	10.90	0.01 b	0.58	(3.15, 0.17) b		10.90
Sewage sludge	500	8.81	25.42	74.21	0.48	(0.45, 18.19) a	(8.52, 59.29, 14.74) a	76.76
	700	11.11	32.17	81.53	0.15	(0.30, 20.35) a	(9.94, 64.37, 16.37) a	50.34
	900	12.15	67.60	100.09	0.09	(0.12, 20.34) a	(9.68, 69.56, 17.52) a	247.51
Palm tree rachis (leaves)	600	10.23	164.73	38.68	0.62	0.53	0.2	39.86
Silica impregnated	600	9.02	140.37	71.39	0.75	1.48	0.11	33.20
Zeolite impregnated	600	9.09	153.28	68.37	0.57	1.94	0.46	76.27
Rice straw	350	-	166.90	18.00	0.51	0.94	0.22	-
	600	-	391.00	27.10	0.60	0.42	0.04	-
Rice straw ($FeCl_3$ modified)	350	-	206.20	21.10	0.42	0.92	0.27	-
	600	-	363.00	28.90	0.56	0.43	0.07	-
Swine manure	350	-	123.50	30.80	0.50	1.03	0.24	-
	600	-	325.80	45.00	0.61	0.45	0.06	-

Swine manure ($FeCl_3$ modified)	350	-	164.40	28.60	0.45	1.02	0.30	-
	600	-	267.60	43.30	0.57	0.56	0.17	-
Rice straw ($FeCl_3$ modified)	450	-	3.40	-	0.61	0.30	0.10	-
Rice straw ($AlCl_3$ modified)	450	-	3.10	-	0.53	0.90	0.20	-
Poultry litter	450	-	10.40	-	0.60	0.30	0.10	-
Poultry litter ($FeCl_3$ modified)	450	-	1.80	-	0.61	0.50	0.10	-
Poultry litter ($AlCl_3$ modified)	450	-	4.70	-	0.45	0.80	0.20	-
Corn straw	450	-	12.60	-	0.53	0.80	0.30	-
Corn straw ($FeCl_3$ modified)	450	-	11.00	-	0.48	0.60	0.30	-
Corn straw ($AlCl_3$ modified)	450	-	11.40	-	0.53	0.90	0.40	-

Methodology

To conduct this review, we adopted a comprehensive approach that encompassed a systematic literature search, rigorous selection criteria, and thorough data extraction and analysis procedures. This methodological framework ensured the inclusion of relevant and high-quality studies that would facilitate a comprehensive understanding of the potential of biochar for mitigating greenhouse gas emissions and nutrient loss in rice paddies.

A. Search Strategy

Our search strategy involved a broad search of academic databases, including PubMed, Web of Science, Scopus, and Google Scholar, as well as a hand-search of reference lists in relevant articles to identify additional sources. To address this gap, we conducted a literature search using the mainstream academic database Web of Science to identify relevant papers on the application of BCs to improve and remediate paddy soils. A total of 1,729 papers were initially obtained using the keywords "BCs and paddy." Based on a review of titles and abstracts, we selected more than 200 papers that closely aligned with the subject matter of this review.

B. Selection Criteria

We established rigorous selection criteria to ensure the inclusion of only the most relevant and high-quality studies in the review. The inclusion criteria were as follows:

1. The study had to be a primary research article that reported on empirical findings.
2. The study had to be written in English.
3. The study had to focus on the application of biochar in rice paddies and its impact on greenhouse gas emissions and/or nutrient loss.

Studies that did not meet these criteria were excluded from the review. Also, review articles, conference proceedings, dissertations, theses, book chapters, and reports were excluded due to their varying quality standards and reporting formats. However, key information from such sources was used to guide the review process.

C. Data Extraction and Analysis

Data extraction involved the collection of key information from the selected studies. For each included study, we extracted data on the study design, location, sample size, type and quantity of biochar used, application method, measurements of greenhouse gas emissions and nutrient loss, key findings, and limitations. This data was tabulated to facilitate comparison and synthesis.

The analysis involved a narrative synthesis of the extracted data, focusing on the impacts of biochar application on greenhouse gas emissions and nutrient loss in rice paddies. We also identified patterns and trends across the studies, noted areas of agreement and disagreement, and highlighted gaps in the current research. Our goal was to produce a comprehensive, evidence-based overview of the potential of biochar for mitigating greenhouse gas emissions and nutrient loss in rice paddies, identifying areas where further research is needed and providing recommendations for future work in this field.

Biochar: Production and Characteristics

Biochar, a carbon-rich product derived from the pyrolysis of organic biomass, has increasingly gained recognition for its potential in mitigating greenhouse gas emissions, enhancing soil fertility, and improving environmental sustainability. Understanding the production and inherent properties of biochar is fundamental to tapping into its potential. Biochar production primarily involves the process of pyrolysis, which is the thermochemical decomposition of organic material in the absence of oxygen or under significantly reduced oxygen concentrations (Lehmann & Joseph, 2015). This process usually occurs at high temperatures ranging between 300 and 1000°C. Pyrolysis results in three main products: biochar, syngas (a mixture of hydrogen and carbon monoxide), and bio-oil. The biochar yield, along with the proportions of the other two by-products, depends on the processing conditions, particularly temperature, heating rate, and residence time, as well as the type of biomass feedstock used.

A diverse array of biomass materials can serve as feedstock for biochar production. These include wood, crop residues such as straw and husks, animal manures, green waste, and other organic materials (Novak & Busscher, 2013). The choice of feedstock significantly influences the properties of the resulting biochar and, consequently, its performance and suitability for specific applications. For instance, biochars produced from woody feedstocks typically exhibit higher carbon content and stability compared to those derived from grasses or manures. Biochar is recognized for its unique physical and chemical properties, which contribute to its functionality when applied to soil. Key properties include:

1. High Porosity and Surface Area: Biochar is characterized by a porous structure with a large surface area, which enhances its capacity for water retention, provides habitat for beneficial soil microbes, and facilitates the adsorption of nutrients and pollutants (Lehmann *et al.*, 2006).

2. High Carbon Content and Stability: The high carbon content and stability of biochar mean that it can persist in soil for centuries or even millennia, thereby sequestering carbon and mitigating greenhouse gas emissions (Lehmann & Joseph, 2015).

3. Nutrient Retention Capacity: Biochar can retain and slowly release essential nutrients, improving soil fertility and crop productivity, and minimizing nutrient leaching (Lehmann *et al.*, 2006).

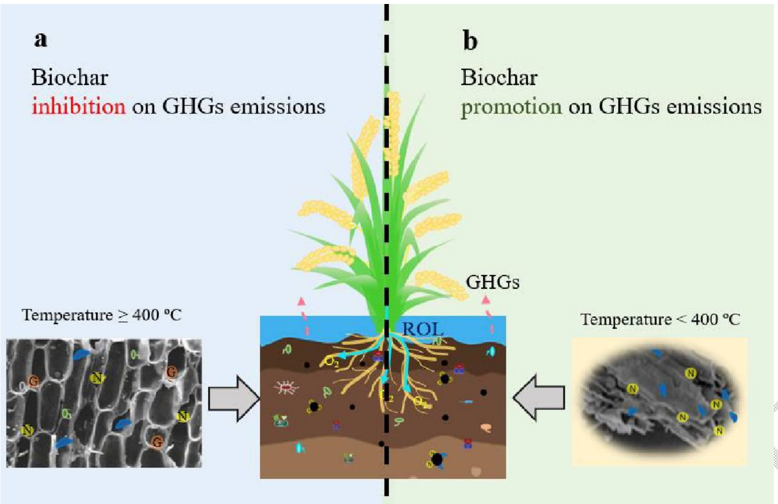

Figure 1: Inhibition (a) and promotion (b) of greenhouse gas emissions by BCs in rice fields.

Greenhouse Gas Emissions from Rice Paddies

In agriculture, rice paddies significantly contribute to greenhouse gas emissions, particularly methane (CH_4) and nitrous oxide (N_2O). It delver deeper into these contributions and their environmental implications. Methane emissions from rice paddies stem from the anaerobic decomposition of organic matter in flooded fields. The microbes involved in this process, known as methanogens, thrive in the oxygen-deprived conditions of flooded rice fields and produce methane as a by-product of their metabolism (Wassmann *et al*., 1993). Furthermore, CH_4 emissions from rice paddies are significantly influenced by management practices. For instance, continuous flooding of rice fields tends to increase methane emissions compared to intermittent flooding (Yan *et al*., 2005). Nitrous oxide emissions from rice paddies mainly occur through the microbial processes of nitrification and denitrification. Nitrification involves the conversion of ammonia to nitrate by aerobic bacteria, while denitrification involves the conversion of nitrate to dinitrogen by anaerobic bacteria. These processes are influenced by factors such as soil pH, temperature, moisture content, and the availability of organic carbon and nitrogen (Shang *et al*., 2011). Additionally, the application of nitrogen fertilizers can boost N_2O emissions, as surplus nitrogen provides substrates for nitrifying and denitrifying bacteria (Cai *et al*., 1997). Several studies have endeavored to quantify greenhouse gas emissions from rice paddies. A study by Sass *et al*. (1992) reported that rice paddies account for approximately 5-20% of total anthropogenic methane emissions. Similarly, Cai *et al*. (1997) found that N_2O emissions from rice paddies account for about 3-5% of total anthropogenic N_2O emissions. These emissions have significant environmental implications. Methane and nitrous oxide are potent greenhouse gases, with 28 and 265 times the global warming potential of carbon dioxide over a 100-year period, respectively (Myhre *et al*., 2013). Therefore, their emissions contribute significantly to global warming and subsequent climate change impacts, such as rising global temperatures, sea-level rise, and increased frequency and intensity of extreme weather events (IPCC, 2014). Furthermore, the increased N_2O emissions can contribute to ozone layer depletion, further exacerbating environmental concerns (Ravishankara *et al*., 2009).

Nutrient Loss in Rice Paddies

Understanding nutrient loss in rice paddies involves evaluating the causes, the impact on crop yield and soil health, and its overall environmental implications. This section aims to provide a comprehensive overview of these aspects. Leaching is one of the primary causes of nutrient loss in rice paddies. This process involves the downward movement of dissolved nutrients through the soil profile beyond the root zone due to excessive rainfall or irrigation. Consequently, essential nutrients such as nitrogen, phosphorus, and potassium are lost from the soil, reducing their availability to the rice plants (Zhang *et al.*, 2014). Erosion, which entails the removal of topsoil by wind and water, is another significant cause of nutrient loss. The process often sweeps away nutrient-rich soil particles, contributing to reduced soil fertility and, consequently, diminished crop yields (Lal, 2001). Volatilization refers to the conversion of solid or liquid substances into gas. In rice paddies, this often involves the transformation of applied nitrogen fertilizers into ammonia gas, leading to nitrogen loss from the soil (Savci, 2012). The rate of volatilization is influenced by factors such as pH, temperature, and the type of fertilizer used. The impact of nutrient loss from rice paddies is multifaceted, affecting crop yields, soil health, and overall environmental sustainability. Firstly, nutrient loss can lead to significant reductions in crop yields. According to Wang *et al.* (2018), nutrient deficiencies associated with nutrient loss can limit rice growth, reduce grain size and number, and hence decrease overall yield. Moreover, nutrient loss can detrimentally affect soil health. The removal of nutrients through leaching, erosion, and volatilization can diminish soil fertility, reduce organic matter content, and impair soil structure, affecting its capacity to support plant growth and maintain productivity over time (Lal, 2001). Given these implications, managing nutrient loss from rice paddies is of paramount importance. It not only enhances agricultural productivity but also contributes to soil conservation and environmental sustainability. In the context of such strategies, the potential role of biochar is worth investigating.

The application of biochar (BC) has been shown to positively impact rice yield, largely through improving soil characteristics, as demonstrated in (Table 2). The data provided shows variability due to differences in feedstocks, pyrolysis temperature, application rate, duration, and soil type. Biochar application led to various outcomes like increased biodiversity, improved soil aeration, pH adjustments, nutrient availability, decreased nutrient leaching, and enhanced microbial activity, contributing to yield increments (Zhang *et al.,* 2012). Biochar derived from rice straw, for instance, increased the yield from +2.82% to +24.56% (Liu *et al.,* 2013). Rice straw biochar, applied at 5, 10, 20 t/ha over four years, led to improved biodiversity, soil aeration, and pH, increasing the yield from +2.82% to 7.47% (Lehmann *et al.*, 2011). In another study, rice straw biochar was applied at 22.5 t/ha for three years, leading to an increase in soil pH, total carbon (TC), and total nitrogen (TN), resulting in a +9.2% to +16.4% yield increase (Glaser, 2002). Biochar derived from wheat straw at 500°C, applied at 0.5–3% w/w for two years, resulted in increased soil pH and nitrogen availability, improving the yield by +1.8% to +7.3% (Baronti *et al*., 2010). Wheat straw biochar produced at 350–450°C and applied at 20 t/ha increased soil organic carbon (SOC), TN, and nutrient availability, resulting in a significant yield improvement of +28.4% (Woolf *et al*., 2010). Rice husk biochar yielded some of the highest yield improvements. When applied to acid sulfate soil, it improved soil pH, nutrient availability, and total bacterial population, resulting in a dramatic yield increase of +41.87% (Biederman & Harpole, 2013). When rice husk biochar was applied at 2% w/w to sandy loam soil, it increased soil nutrient availability, leading to an impressive yield improvement ranging from +18.58% to +35.1% (Jones *et a*l, 2011). Biochar produced from other feedstocks such as bamboo chips, cassava straw, chicken litter, and sewage sludge also showed promising results. For instance, chicken litter biochar application resulted in a massive +86.44% yield increase (Agegnehu *et al*., 2016) and sewage sludge biochar yielded the largest yield increase ranging from +148.8% to +175.1% (Jin, H., 2010). Although biochar effects were generally positive, results varied depending on factors such as application rate, pyrolysis temperature, feedstock type, and soil properties. Understanding these interactions and optimizing biochar application methods is crucial to fully utilize its potential in enhancing rice yield. It's also important to further investigate the long-term impacts of biochar application on soil health and crop yield stability (Jeffery*etal*.2011).

Table 2. Effect of BC application on the improvement of rice yield.

Feedstocks	**Pyrolysis Temperature (°C)**	**Application Rate**	**Time (years)**	**Soil Type/Texture**	**Main Impact Factors**	**Yield Increase (%)**
Rice Straw	350–500	5, 10, 20 t/ha	4	Sandy loam	Increased biodiversity, soil aeration, soil pH	+2.82% - 7.47%
Rice Straw	500	22.5 t/ha	3	-	Increased soil pH, TC, TN	+9.2% - +16.4%
Rice Straw	550	10.5 t/ha	2	Gley paddy	Increased soil pH, SOC, available P and K	+8.5% - +10.7%
Wheat Straw	500	0.5–3% w/w	2	-	Increased soil pH, soil N availability	+1.8% - +7.3%
Bamboo Chips and Rice Straw	600	22.5 t/ha	2	Clay loam	Increased NO_3^--N content of rhizosphere soil	+19.8% - +21.6%
Cassava Straw	300–500	20, 30 t/ha	-	Ultisols	Improved soil pH, SOC, TN, soil microbial C and N	+10.46% - +10.56%
Wheat Straw	350–450	20 t/ha	-	Anthrosol	Increased SOC, TN, nutrient availability	+28.4%
Rice Husk	500	4 t/ha	-	Acid sulfate soil	Improved soil pH, nutrients (K, P, Ca, Mg), total bacterial population	+41.87%
Wheat Straw	550–600	5, 20, 40 t/ha	-	Silty loam	Decreased N and P leaching loss, increased N use efficiency	+4.42% - +16.89%
Rice Straw	450–500	1.8, 3.6 mg/ha	-	Saline–alkaline soil	Increased P availability and retention, increased CEC	+3.66% - +8.54%
Rice Straw	600	15, 30, 60 t/ha	-	Clay and sand	Improved soil pH, SOC, nutrient availability, N use efficiency	+10.13% - +24.56%
Rice Husk	300, 500, 600	2% w/w	-	Sandy loam	Increased soil nutrient availability	+18.58% - +35.1%
Rice Straw	-	20, 40 t/ha	-	Dark-yellow	Reduced N loss and improved N use efficiency	+1.67% - +5.54%

Wheat/Rice/Maize Straw	550	2% w/w	-	-	Enhanced soil invertase, phosphatase, urease for C, N, and P mineralization	+51.05% - +102.03%
Rice Husk	500	10, 20 t/ha	-	Clay	Increased pH, CEC, OC, N, P, and K availability	+52.2% - +65.4%
Rice Husk	600	1% w/w	-	Slightly acidic	Increased essential elements and water usage efficiency	+11% - +19%
Chicken Litter	-	5 t/ha	-	Sandy loam	Increased soil pH, TC, TP, TN, available P and exchangeable N	+86.44%
Sewage Sludge	550	5, 10% w/w	-	Sandy loam	Increased soil pH, TN, SOC, available nutrients	+148.8% - +175.1%
Cassava Straw	-	30 t/ha	-	Ultisol	N uptake was associated with enhanced activities of N metabolism enzymes	-
Wheat Straw	500	24, 48 t/ha	3-4	Granite red soil	Mortierella and Westerdykella promoted TOC degradation	-
Wheat Straw	350–550	20, 40 t/ha	-	Sandy loam	Increased dehydrogenase and alkaline phosphatases, decreased β-glucosidase	-
Rice Straw	500	24 t/ha	-	Stagnic anthrosol	Stimulated microbial use of N-rich substances, such as amino acids	-
Rice Husk	-	1, 2, 5, 10% w/w	-	Riparian soil	Enhanced P mineralization and reduced N leaching	-

Role of Biochar in Mitigating Greenhouse Gas Emissions and Nutrient Loss

Biochar holds great promise in addressing the challenges of greenhouse gas emissions and nutrient loss in rice paddies. It involves roles of biochar in mitigating these issues and evaluates empirical evidence supporting these theories. Biochar's potential to reduce greenhouse gas emissions is associated with its unique physicochemical properties. Its porous structure and high surface area can provide habitats for methanotrophs-microbes that consume methane-thereby reducing CH_4 emissions (Liu *et al*., 2019). Moreover, biochar can enhance soil aeration, disrupting the anaerobic conditions that favor methane production (Zhang *et al*., 2010). For N_2O emissions, biochar can indirectly reduce its production by influencing soil pH and moisture content. Biochar has been found to increase soil pH, which can inhibit nitrification and denitrification processes responsible for N_2O emissions (Cayuela *et al*., 2013). Additionally, improved soil structure and water-holding capacity due to biochar application can decrease soil water saturation, further reducing conditions favoring N_2O production (Singh *et al*., 2010). Biochar is also thought to minimize nutrient loss through several mechanisms. Firstly, it can enhance soil retention of nutrients due to its high cation exchange capacity (CEC), reducing nutrient leaching (Lehmann *et al*., 2011). Secondly, the porous structure of biochar can help to mitigate soil erosion by improving soil aggregate stability (Liu and Zhang, 2012). Additionally, biochar can reduce nitrogen loss through volatilization. Biochar's alkaline pH can help to retain ammonia, a form of nitrogen lost through volatilization, thus preserving soil nitrogen (Spokas *et al*., 2009). Several empirical studies have examined the efficacy of biochar in mitigating greenhouse gas emissions and nutrient loss. For instance, Zhang *et al.* (2010) reported a significant decrease in methane emissions from rice paddies following biochar application, attributed to improved soil aeration and increased methanotroph activity. Similarly, Cayuela *et al.* (2013) observed reduced N_2O emissions following biochar application to a tropical soil, correlating with changes in soil pH and moisture content. For nutrient loss, a study by Lehmann *et al.* (2011) found that biochar application reduced leaching of nitrate and phosphate in sandy soils.

Potential Ecological Risks

While biochars (BCs) have demonstrated immense promise in tackling environmental issues within rice fields and boosting rice yields, there are potential challenges associated with their use. Factors such as the origin of the feedstock, conditions of pyrolysis, and modification techniques of BCs can lead to significantly diverse performance characteristics, introducing a degree of unpredictability. This could potentially undermine the advantages of using BCs for enhancing and rehabilitating rice fields, and might even precipitate detrimental consequences. For example, harmful substances might be released, greenhouse gas emissions might escalate, pollutants might be secondarily emitted, and the biodegradation of pesticides might be obstructed. Moreover, the growth and development of both rice plants and microorganisms might be hindered. Consequently, the potential ecological risks stemming from the employment of BCs in paddy cultivation systems remain a pressing concern in current discussions.

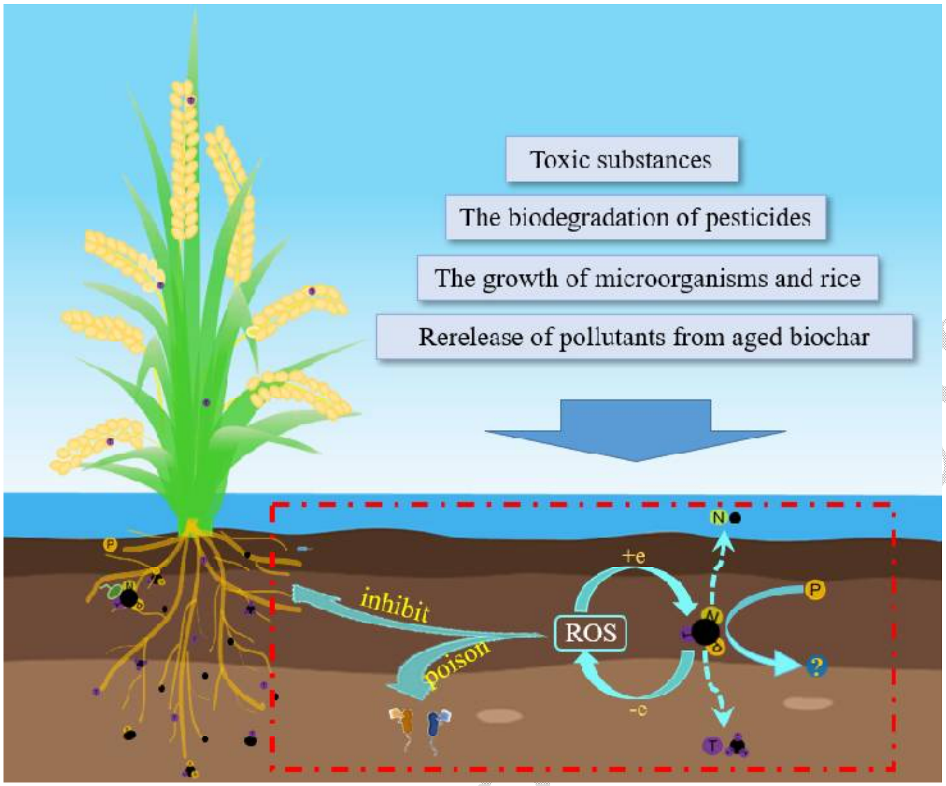

Figure 2: Potential risks of BC application in paddy fields.

Conclusion

Biochars (BCs) have demonstrated considerable potential in mitigating global environmental challenges within rice cultivation environments, while simultaneously enhancing rice yields. Thus, the utilization of BCs is increasingly viewed as an eco-friendly, cost-effective, and sustainable strategy for the enhancement and restoration of paddy fields. Factors such as the type of biomass used, the pyrolysis temperature, and the method of modification play crucial roles in shaping the performance attributes of BCs. The application of BCs, or their modified counterparts with varying performance characteristics, can foster rice yield increases and reduce greenhouse gas emissions (for instance, CO_2, N_2O, and CH_4). This is achieved by improving soil physical and chemical properties, nurturing microbial communities, providing nutrient sources, and curbing nutrient losses. Even though BCs are finding more use as amendments for paddy remediation, potential ecological risks associated with BCs in rice fields warrant further exploration.

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