

Article

Impact of Biochar and Its Modification on Heavy Metals and Drought in Rice: Knowns, Unknowns, and Research Directions

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Abstract

Rice, a staple food for over half of the global population, faces significant threats from environmental stressors such as heavy metal (HMs) contamination, notably cadmium (Cd) and arsenic (As), and increasing drought severity, exacerbated by climate change. These challenges not only compromise rice yield and quality but also pose serious food safety risks due to HM accumulation in grains, endangering human health. Modified biochar (MBC), a carbon-rich material derived from the pyrolysis of organic matter with post-treatment enhancements, has emerged as a strategy to address these dual stressors. MBC application (typically 5–20 t ha^{−1}) reduces Cd and As bioavailability in paddy soils by 40–60% and decreases metal accumulation in rice grains by 20–85% compared to the control. Under drought conditions, MBC improves soil water-holding capacity by 11–45% and enhances crop water use efficiency by 15–24%, leading to yield improvements of 20–50% under moderate water deficit. Furthermore, MBC supports nutrient availability, fosters robust root systems, and enhances soil aeration, collectively improving rice growth under adverse conditions. Beyond its agronomic benefits, MBC provides a framework for addressing multiple challenges by integrating scientific innovation, policy alignment, and community participation. This approach not only reduces heavy metal toxicity and strengthens plant resilience but also enhances food security and advances Sustainable Development Goals (SDGs 2, 3, 4, 12, 13, 15, 17). By promoting environmentally sustainable agriculture and contributing to climate change mitigation, MBC represents a transformative tool for ensuring sustainable rice production in the face of global challenges.

Keywords: modified biochar; rice; drought; heavy metals; cadmium; arsenic; climate change



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1. Introduction

Rice (*Oryza sativa* L.) is a staple food of global significance, deeply rooted in the diets, cultures, and economies of more than half the world's population, particularly in Asia [1]. Its historical legacy is marked by its role in the development of civilizations, especially in ancient China and India, where rice cultivation began over 7000 years ago [2,3]. This extensive history underscores the interconnectedness of rice and human development, with rice terraces and traditional farming methods still viewed as symbols of cultural heritage in countries like the Philippines and Indonesia [4]. The economic significance of rice is further highlighted by its role in supporting millions of smallholder farmers, making it a central

commodity in global agricultural trade, particularly in major rice-producing nations such as China, India, and Indonesia [1].

Nutritionally, rice is a rich source of complex carbohydrates, vitamins and minerals, supporting gluten-free diets and global culinary diversity [5–7]. It contributes to food security and economic stability in developing countries, with rising demand due to population growth [8]. However, climate change impacts like droughts and erratic monsoons threaten the rice yield and quality [9,10]. Addressing these pressure requires innovations in water-efficient farming and climate-resilient practices to preserve rice's role in global food security and cultural heritage [11,12].

1.1. Effect of Heavy Metals and Drought on Rice Production

Rice is not only a global staple food but also a crucial crop that supports the livelihoods of millions of people [13]. However, its production faces multifaceted challenges, including the presence of heavy metals, such as Cd and As, in soil and water, as well as the increasingly erratic and severe impacts of drought [14,15]. In this exploration, we delve into the pressing threats that heavy metals and drought pose to rice production, emphasizing their detrimental effects on yield, quality, and overall food security [16]. The term heavy metals (HMs) refers to potentially toxic elements, including cadmium (Cd), arsenic (As), lead (Pb), mercury (Hg), and chromium (Cr). While As is technically a metalloid, it is included here due to its similar environmental behavior and toxicity. We acknowledge that some elements like copper (Cu) and iron (Fe) are essential micronutrients, but their elevated concentrations also become toxic to plants.

1.1.1. Heavy Metals in Rice Production: A Looming Menace

Cadmium (Cd) and arsenic (As) are two of the most toxic HMs, which pose a severe threat to rice production and food safety [17], Cd enters rice fields primarily through anthropogenic activities, including industrial emissions, mining, and the use of contaminated irrigation water [18,19]. Meanwhile, As is often naturally occurring, and its presence in rice fields is influenced by geological factors, as well as human activities such as mining, industrial processes, and the use of arsenic-containing pesticides [20]. Both HMs accumulate in rice grains, posing serious health risks to consumers [21], including cancer, kidney damage, and cardiovascular diseases [22,23]. These contaminants disrupt physiological processes in rice plants, leading to reduced growth, lower yields, and poor grain quality [24,25]. The detailed mechanisms of Cd and As toxicity, their effects on rice physiology, and their impact on grain quality are discussed in detail in Section 2.1.

1.1.2. Drought: A Persistent and Worsening Threat

Drought, characterized by a prolonged period of water scarcity, poses an escalating threat to rice production due to climate change-induced alterations in precipitation patterns [26]. Drought significantly reduces rice yields by limiting water availability during critical growth stages. Water stress leads to poor tillering, reduced grain filling, and ultimately, lower overall production [15]. Asia, where a significant portion of the world's rice is grown, is particularly vulnerable to increasing drought severity and frequency [27]. Furthermore, drought can result in the accumulation of toxic compounds and a reduced nutrient content in rice grains, compromising food quality and safety [10]. The physiological mechanisms of drought stress, its effects at different growth stages, and yield reduction percentages are elaborated in Section 2.2.

1.2. Modified Biochar as a Potential Mitigation Strategy

Biochar (BC) is a carbon-rich material produced through pyrolysis of organic biomass. Its stable carbon structure, high porosity and extensive surface area make it valuable for

improving soil quality and mitigating environmental stresses. Table 1 shows the resources, preparation conditions and basic physicochemical properties of BC. BC is prepared from agricultural wastes such as rice, wheat, and tobacco straw, and pyrolyzed at 350–700 °C under anaerobic conditions, with high alkalinity and rich in nitrogen, phosphorus and various cations. Modified biochar (MBC), produced through chemical, physical, or biological modifications of raw BC, exhibits enhanced properties including increased surface area, abundant functional groups, and improved cation exchange capacity (CEC) [28]. These enhancements make MBC more effective in mitigating these challenges compared to unmodified biochar [29].

MBC mitigates HM toxicity by immobilizing Cd, and As through adsorption, complexation, and precipitation mechanisms, preventing their uptake by rice plants and reducing their bioavailability in soil [30,31]. It also improves soil water retention, nutrient availability, and soil aeration, enhancing rice resilience under drought conditions [32,33]. Additionally, MBC buffers soil pH, supports beneficial soil microorganisms, and contributes to long-term carbon sequestration [34,35]. The detailed mechanisms by which MBC mitigates HMs and drought stress are discussed in Sections 3.6 and 3.7. The BC properties shown in Table 1 were previously used in rice to minimize these stresses.

Table 1. Biochar properties after pyrolysis at different temperatures used in rice field.

BC Source	Pyrolysis °C	pH	Ash %	OC g/kg	TN g/kg	TP g/kg	T Cd mg/kg	T Cu mg/kg	CEC cmol/kg	Reference
Rice Straw	700	10.63	36.81	510.38	10.7	4.29	0.25	42.08	43.39	[36]
Rice Husk	700, 2 h	10.63	36.81	510.38	10.7	4.29	0.25	42.08	43.39	[37]
Rice Straw	700, 2 h	10.05	30.65	490.59	6.8	4.22	0.09	29.66	20.71	[37]
Rice Straw	450, 2 h	10.0	22.5	42.3%	1.5%	0.3%	-	-	-	[38]
Wheat Straw	350–550	10.4		467	5.9 g/kg		0.2		21.7	[39]
Bean Stalk	500, 8 h	9.2		44.5%	1.85%	0.37%	1.5×10^{-4}		27.5	[40]
Rice Stalk	500, 8 h	10.5		27.4%	1.26%	0.46%	1.0×10^{-4}		32.1	[40]
Sewage Sludge	500, 3 h	7.19		12.38%	0.52%	9.74×10^{-3}	0.42	27.50		[41]
Wheat Straw	350–550	10.4	20.8	467	5.9		0.02		21.7	[42]
Wheat Straw	485	10.4		467	5.9	14.4	0.03			[43]
Tobacco Stalk	450, 2 h,	9.7	22.37	488	27.8	2.22	4.31		31.94	[44]
Dead Pig BC	650, 2 h,	9.34	47.89	258	36.4	83.30	0.11		20.75	[45]

1.3. Objectives of the Review Paper

Assessing the Impact of Heavy Metals (Cd and As) on Rice Production: This review evaluates how cadmium and arsenic uptake affects rice yield, quality, and plant health,

aligning with UN SDG 2 (Zero Hunger) and SDG 3 (Good Health and Well-being) by promoting food safety and sustainable crop production. The objective includes examining how drought alters rice physiology, reducing productivity and food security, thus supporting SDG 2 through resilient food production and SDG 13 (Climate Action) by emphasizing adaptation to climate-related stresses. This review investigates the compounded effects of drought and heavy metal stress on rice, contributing to SDG 2 by addressing factors that reduce food productivity under challenging conditions. This study assesses biochar's effectiveness in alleviating combined heavy metal and drought stress in rice, supporting SDG 12 (Responsible Consumption and Production) and SDG 13 by promoting environmentally sustainable soil management practices. By providing an updated review of current studies, this paper aims to support SDG 4 (Quality Education) through knowledge dissemination and SDG 17 (Partnerships for the Goals) by highlighting collaborative research. This objective seeks to identify areas for further study, guiding future research in sustainable rice farming and contributing to SDG 2 and SDG 15 (Life on Land) by advancing practices for sustainable agriculture. Ultimately, the review aims to encourage resilient and eco-friendly rice farming practices, advancing SDG 2 by promoting sustainable food production and SDG 13 through climate-resilient agriculture. This paper addresses critical issues in rice production under heavy metal and drought stress, proposing modified biochar as a viable mitigation strategy for resilient agricultural practices aligned with the UN SDGs.

2. Rice Vulnerability to Stress

2.1. Impact of Heavy Metals on Rice Plants and Grain Quality

The impact of HMs, specifically Cd and As, on rice plants and grain quality is a critical concern in agricultural and food security contexts. Not only did these HMs affect rice quality but also its range in soil affects rice germination, growth, yield, and quality of rice kernels (Table 2). These HMs contaminate rice fields through various sources, including industrial emissions, mining activities, and the use of contaminated irrigation water, posing significant threats to both crop health and human well-being [46]. Cadmium is a highly toxic heavy metal that severely inhibits the growth of rice plants. It interferes with essential physiological processes such as nutrient uptake, photosynthesis, and transpiration [17]. Consequently, rice plants exposed to elevated levels of Cd often exhibit stunted growth and lower yields, reducing overall productivity [18]. Further, Cd tends to accumulate in rice roots, causing structural damage and reducing the plant's ability to absorb essential nutrients, particularly Fe and Zn. This can lead to nutrient deficiencies and further impair crop growth and grain quality [47]. More, Cd contamination leads to smaller and lighter rice grains, affecting both grain quality and market value. Smaller grains also have lower milling yields, reducing the overall rice product [48]. Furthermore, perhaps the most significant concern is the accumulation of Cd in rice grains, particularly in the outer layers. This poses a direct risk to human health when contaminated rice is consumed, as cadmium is a known carcinogen and leads to kidney and bone damage over time [17]. Supplementary, elevated Cd levels cause discoloration of rice grains, leading to dark spots and streaks. This discoloration reduces the visual appeal and market value of the rice. Furthermore, Cd-contaminated rice has an undesirable taste, impacting consumer preferences [43].

Arsenic is another hazardous heavy metal that inhibits rice plant growth [20]. Elevated levels of As can induce stress responses in plants, leading to reduced shoot and root growth. This results in overall yield reductions [20]. Moreover, As disrupts various physiological processes in rice plants. It interferes with photosynthesis, nutrient uptake, and water transport, leading to reduced overall plant health and productivity [49]. Unlike Cd, which primarily accumulates in the bran, arsenic terminate accumulates in both the bran and the endosperm of rice grains. This makes it a pervasive threat to grain quality

and safety [50]. Correspondingly, consumption of rice grains containing elevated levels of arsenic poses serious health risks to humans. Chronic exposure to arsenic is associated with skin lesions, cardiovascular problems, and an increased risk of cancer, among other health issues. Vulnerable populations, such as children and pregnant women, are particularly at risk [22,24]. In addition, As-contaminated rice may exhibit reduced grain quality, affecting factors such as appearance, cooking quality, and taste. This can lead to lower consumer acceptability and market value [51]. In conclusion, both cadmium and arsenic contamination in rice fields have detrimental effects on rice plants and grain quality. These heavy metals not only inhibit plant growth and reduce yield but also compromise grain safety and marketability [14]. Addressing heavy metal contamination in rice cultivation is essential not only for agricultural productivity but also for safeguarding human health and food security [48]. Mitigation strategies such as soil remediation, phytoremediation, and the use of amendments like biochar can play a crucial role in minimizing heavy metal exposure in rice cultivation [46].

Table 2. Major HMs' available forms in soil, ranges in plants and effects on rice.

Sr	Heavy Metal	Symbol	Range in Plant ug/g Dry Weight	Available Form in Soil	Effect on Rice	Reference
1	Arsenic	As	0.02–7.0	Inorganic forms, i.e., arsenate As(V), arsenite As(III)	Reduces plant height, shoot biomass, grain and straw yield, straight head disease	[52]
2	Cadmium	Cd	0.10–2.40	Free metal, oxides, and various salts	Inhibits oxidative reactions and nitrogen metabolism, reduces yield	[53]
3	Chromium	Cr	0.2–1	Cr(III), Cr(VI)	Reduces root development, decreases grain weight, decreases yield	[54]
4	Copper	Cu	4–15	Free ions (Cu^{2+}), organic complexes, and insoluble mineral forms	Decreases seed germination, represses plant growth, reduces root and shoot length, leaf chlorosis	[53,55]
5	Mercury	Hg	0.005–0.02	Elemental mercury, organic and inorganic mercury compounds	Decreases plant height, tiller, panicle formation, and yield	[52]
6	Lead	Pb	1–13	Lead minerals, organic complexes	Inhibits seed germination, fresh and dry biomass, leaf area, chlorophyll and growth	[54]

2.2. Effects of Drought Stress on Rice Growth and Yield

Drought stress leads to reduced water availability in the soil, causing water stress in rice plants. This results in stunted plant growth, with shorter stems and reduced plant heights compared to well-irrigated conditions [27]. Moreover, drought stress can limit the number of tillers (side shoots) formed by the rice plant. Fewer tillers mean fewer panicles and ultimately fewer grains per plant [56]. Further, as a water conservation mechanism, rice plants often exhibit leaf rolling under drought stress. This reduces the leaf surface area exposed to sunlight and helps minimize water loss through transpiration [33]. Similarly, drought stress during the critical reproductive stage can lead to the damage of flowers and

spikelets, resulting in fewer panicles. This directly reduces the possible number of grains per plant [15]. Likewise, water deficit stress disrupts the grain-filling process. Rice grains may be smaller, less plump, and lighter in weight due to reduced starch accumulation [10]. Additional, drought stress causes incomplete panicle development, leading to empty or partially filled grains. This further reduces grain yield and quality [51].

Effects of Drought Stress on Physiological Processes

Drought stress hampers the rice plant's ability to conduct photosynthesis, as water is essential for this process. Reduced photosynthesis leads to lower carbohydrate production, limiting the energy available for growth and grain development [56]. Comparable, drought stress induces stomatal closure to reduce water loss through transpiration. While this conserves water, it also limits the plant's ability to take up essential nutrients, resulting in nutrient deficiencies [33]. Similarly, this stress alters the balance of plant hormones, including abscisic acid (ABA) and gibberellins (GA). ABA increases under drought conditions, leading to stomatal closure and reduced growth, while GA levels decrease, affecting cell elongation and overall plant growth [57]. In addition, water stress leads to the accumulation of reactive oxygen species (ROS) in plant cells, causing oxidative stress. This damages cell membranes, proteins, and DNA, impacting plant health and vitality [33]. Identically, drought stress limits root growth, reducing the plant's ability to explore the soil for water and nutrients. Shallow root systems are less efficient at extracting water from deeper soil layers, exacerbating water stress [12,58].

In a nutshell, drought stress significantly impacts the rice growth and yield at different growth stages (Table 3). It leads to stunted growth, reduced tillering, poor grain filling, and other morphological changes, which ultimately result in a lower grain yield [27]. Additionally, drought stress disrupts critical physiological processes, such as photosynthesis, nutrient uptake, and hormonal regulation, further compromising the plant's ability to cope with adverse conditions [15]. Effective strategies to mitigate the effects of drought on rice production include the development of drought-tolerant rice varieties, improved water management practices, and use of soil amendments like biochar to enhance water retention in rice fields [33,57].

Table 3. Effect of drought stress on rice yield at different growth stages.

Sr.	Drought Stress Stage	Rice Variety	Experiment	Yield Reduction	Reference
1	Seedling stage	Pathum Thani 1	Greenhouse	40.98%	[59]
2	Tillering stage	Pathum Thani 1	Greenhouse	35.89%	
3	Flowering stage	Pathum Thani 1	Greenhouse	50.08%	
4	Seedling stage	Khao Dawk Mali 105	Greenhouse	31.11%	
5	Tillering stage	Khao Dawk Mali 105	Greenhouse	18.63%	
6	Flowering stage	Khao Dawk Mali 105	Greenhouse	25.76%	[33]
7	Tillering stage	Huanghuazhan	Field	33.62%	
8	Jointing booting stage	Huanghuazhan	Field	33.74%	
9	Heading flowering stage	Huanghuazhan	Field	27.49%	
10	Grain filling stage	Huanghuazhan	Field	17.62%	

Table 3. Cont.

Sr.	Drought Stress Stage	Rice Variety	Experiment	Yield Reduction	Reference
11	Mild drought at heading stage	Hanyou113	Pot	14.9%	[60]
12	Mild drought at heading stage	Huanghuazhan	Pot	30.8%	
13	Mild drought at heading stage	Zhonghan3	Pot	12.8%	
14	Moderate drought at heading stage	Hanyou113	Pot	32.9%	
15	Moderate drought at heading stage	Huanghuazhan	Pot	33.7%	
16	Moderate drought at heading stage	Zhonghan3	Pot	22.9%	
17	Severe drought at heading stage	Hanyou113	Pot	53.6%	
18	Severe drought at heading stage	Huanghuazhan	Pot	45.6%	
19	Severe drought at heading stage	Zhonghan3	Pot	30.7%	
20	Flowering stage	YLY6	Field	23.2%	[61]
21	Flowering stage	HY113	Field	24.0%	

2.3. Synergistic Effects in Rice

Both stresses have a synergistic impact on rice plants, significantly affecting plant physiology and development [62]. For instance, Cd competes with essential nutrients like Fe and Zn, exacerbating nutrient imbalances and deficiencies [38]. In drought-stressed environments, where water and nutrients are already limited, this disruption leads to stunted growth, fewer tillers, and poor overall development [60]. The combined stress also impairs photosynthesis and reduces carbohydrate production, further affecting grain filling and grain quality [31].

Research supports the severe impact of these combined stressors. Rizwan et al. [38] found that Cd contamination coupled with drought stress resulted in a significant reduction in rice biomass and photosynthesis, with increased Cd accumulation in rice tissues. Ref. [63] demonstrated that drought intensified As uptake, affecting root and shoot As concentrations, while it was reported that the combined stress reduced grain yield by disrupting nutrient and water relations [34]. Further studies by Irshad et al. [31] and Mondal et al. [20] showed how drought exacerbates Cd's effect on root architecture and grain quality, highlighting the importance of mitigating both HMs and drought stress to ensure sustainable rice production. The detrimental effects of these stressors extend to lower rice yields, posing significant risks to food security and farmer livelihoods, particularly in regions that rely heavily on rice as a staple crop [48]. These findings emphasize the need for strategic interventions to combat these stressors, especially in vulnerable regions.

Synergistic Effects on Physiological and Biochemical Mechanisms

The synergistic effects of HMs combined with drought stress in rice result from a combination of physiological and biochemical disruptions, which significantly amplify the negative impacts on plant growth and development shown in Figure 1. One crucial physiological response involves impaired water uptake and nutrient transport. Drought stress triggers stomatal closure to conserve water, reducing transpiration and limiting nutrient movement [51]. Simultaneously, heavy metals damage root structures and disrupt ion transport, intensifying water stress [52]. For instance, Cd competes with essential nutrients, worsening nutrient imbalances under drought conditions [37]. Additionally, both drought and heavy metals increase the production of reactive oxygen species (ROS), leading to oxidative stress, cellular damage, and impaired metabolic processes [51]. This combination further reduces photosynthesis as limited water availability and heavy metal

interference with chlorophyll production and photosynthetic enzymes diminish energy production and overall plant growth [34].

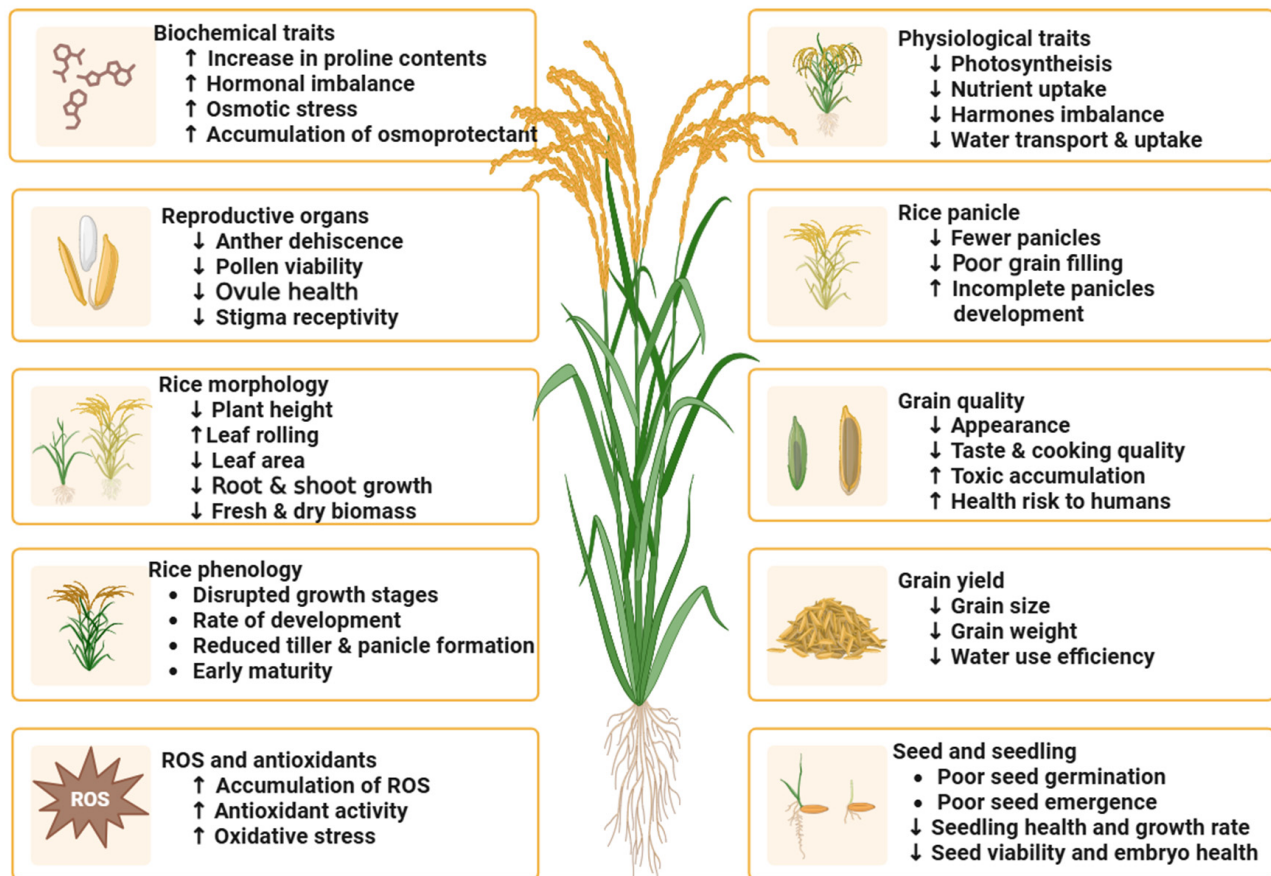


Figure 1. Synergistical effect of HMs and drought on rice plant.

Biochemical disruptions caused by these combined stressors also lead to nutrient imbalances and hormonal changes. Heavy metals interfere with the uptake of essential nutrients, while drought further restricts nutrient mobility, resulting in severe deficiencies that hinder rice development [49]. Heavy metal exposure, particularly Cd, alters root morphology, leading to shallower root systems that restrict the crop ability to access water and nutrients from deeper soil layers, a crucial factor during drought [64]. Drought also induces hormonal changes, especially in ABA, which regulates water stress responses like stomatal closure [57]. When heavy metals disrupt these hormonal processes, the crop ability to cope with drought worsens. These combined physiological and biochemical effects result in a lower grain yield, poorer grain quality, and heightened risks to food security in rice-dependent regions [62]. Addressing these synergistic stressors requires integrated strategies, including soil remediation, improved water management, and the development of drought-resistant rice varieties [62].

2.4. Challenges to Food Security and Livelihoods

The combined effects of heavy metal contamination and drought present severe challenges to food security and livelihoods, particularly in regions dependent on rice production, and directly hinder the achievement of several United Nations Sustainable Development Goals (SDGs) [65]. Heavy metals disrupt nutrient uptake and damage root structures, while drought exacerbates these issues by restricting water availability [64,66]. This leads to stunted plant growth and reduced yields, directly impacting SDG 2: Zero Hunger, which aims to end hunger, achieve food security, and promote sustainable agricul-

ture [67]. Lower yields result in decreased rice availability, threatening food security for millions, especially in Asia, where rice is a dietary staple [20]. Additionally, these combined stressors negatively affect the livelihoods of farmers, many of whom depend on rice as a primary source of income, aligning with the goals of SDG 1: No Poverty. As rice yields decline, farmers face economic hardship, increasing their vulnerability to poverty and limiting their capacity to invest in more sustainable practices [68].

The quality of rice grains is also severely impacted by the combined effects of heavy metals and drought, further affecting SDG 3: Good Health and Well-Being [68]. Heavy metals like Cd and As accumulate in rice grains, posing significant health risks to consumers through chronic exposure to toxic elements, which leads to illnesses such as cancer and organ damage [17]. In addition, drought leads to smaller, less nutritious grains, reducing the nutritional value of rice and undermining efforts to ensure healthy lives. The environmental impacts, such as soil degradation and contamination of water sources through heavy metal leaching, threaten SDG 6: Clean Water and Sanitation and SDG 15: Life on Land, as degraded soils and polluted water systems harm ecosystems and reduce agricultural productivity [69]. Soil degradation not only diminishes land fertility but also requires costly remediation efforts, impeding progress toward SDG 12: Responsible Consumption and Production, which promotes sustainable land management [67]. Addressing these challenges through holistic strategies—such as soil remediation, improved water management, and the development of drought-tolerant rice varieties—supports the goals of SDG 13: Climate Action, encouraging adaptive practices to build resilience in the face of climate-related stressors [27,70]. In conclusion, the intertwined effects of HMs and drought stress highlight the urgent need for integrated approaches to mitigate their impact, directly aligning with several UN SDGs, including food security, health, environmental sustainability, and poverty alleviation.

3. Biochar and Its Modifications

BC is a carbon-rich material produced through the pyrolysis of organic biomass under limited oxygen conditions [71]. The research on modified BC shows it enhancing with every passed year due to its beneficial aspects (Figure 2). This process involves heating biomass, such as agricultural residues or wood, to temperatures typically between 300 °C and 700 °C, resulting in the decomposition of organic components into solid (BC), liquid (bio-oil), and gaseous products [72]. The specific conditions of pyrolysis, including temperature, heating rate, and residence time, significantly influence the yield and properties of the resulting biochar [73]. Slow pyrolysis, characterized by lower temperatures and longer residence times, is commonly employed to maximize biochar production [74]. The resulting biochar possesses a porous structure and high surface area, attributes that contribute to its effectiveness in soil amendment applications [75]. To enhance the functional properties of BC, various modification techniques are applied, transforming it into MBC. Chemical modifications involve treatments with acids, bases, or oxidizing agents to introduce functional groups that improve adsorption capacities [76]. Physical modifications, such as steam activation or microwave treatment, increase surface area and porosity, enhancing the material's reactivity [74]. Biological modifications incorporate microbial inoculation to augment nutrient availability and promote beneficial microbial activity [77]. These strategies collectively enhance MBC effectiveness in environmental remediation and agricultural applications.

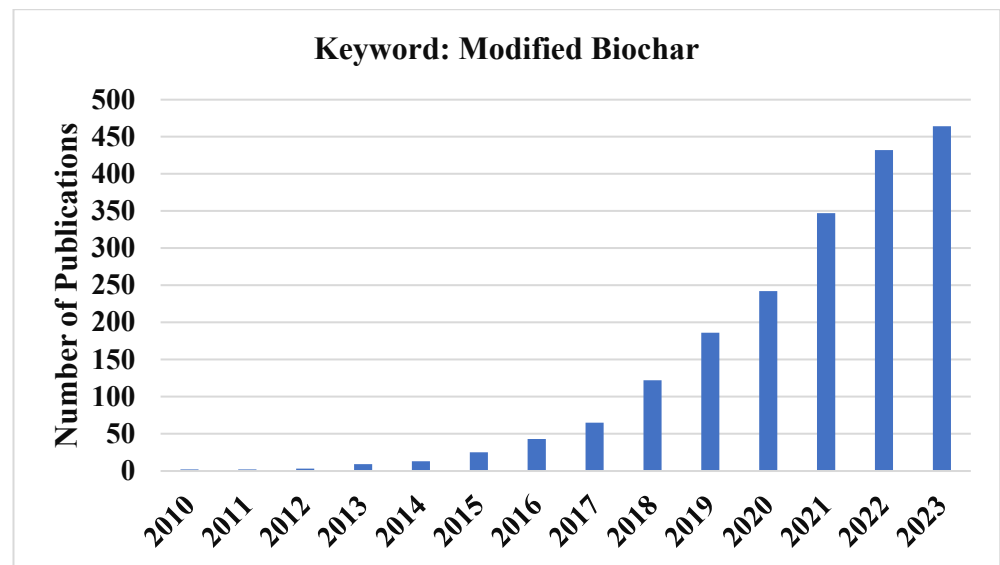


Figure 2. Number of peer-reviewed articles indexed in PubMed that include the term “modified biochar” across the years.

In the context of rice cultivation, MBC offers significant advantages in mitigating drought stress and heavy metal contamination. Its enhanced water retention capabilities improve soil moisture availability, thereby supporting rice growth during periods of water scarcity [31]. Additionally, MBC-increased cation exchange capacity facilitates the immobilization of heavy metals such as cadmium and arsenic, reducing their bioavailability and subsequent uptake by rice plants [45]. This reduction in heavy metal accumulation in rice grains contributes to improved food safety and crop quality [34]. Furthermore, the application of MBC has been associated with enhanced nutrient availability and soil fertility, leading to increased rice yields [39]. By addressing both abiotic stress factors and soil contamination, MBC serves as a valuable tool in sustainable rice production systems.

3.1. Various Sources of Biochar

There are numerous organic natural waste residues as a source of BC (Figure 3). But the selection of feedstocks for MBC production significantly influences its final properties, such as adsorption capacity, porosity, CEC, and nutrient retention. MBC derived from wood feedstocks, such as wood chips, tree pruning, and sawdust, is characterized by a high carbon content and porosity [75]. The chemical modification of wood-based biochar (e.g., acid or base treatments) further increases its surface functional groups, enhancing its ability to adsorb toxic metals such as Cd and As and reduce their bioavailability [74]. Additionally, modified wood-derived BCs improve soil moisture retention and enhance drought resistance, making them effective for crop resilience under water stress [34]. For instance, hardwood-derived MBC has shown a superior CEC and heavy metal immobilization compared to unmodified biochar, making it particularly suitable for rice paddies facing metal contamination and drought [45]. Agricultural residues like rice husks, wheat straw, and sugarcane bagasse are widely used for MBC production. Through chemical or physical modifications, these feedstocks produce MBC with an enhanced surface area and functional groups that improve the adsorption of heavy metals and nutrient retention in soils [78]. For instance, acid-modified rice husk biochar demonstrates high efficiency in immobilizing arsenic and enhancing water-holding capacity, making it particularly effective in rice cultivation under combined HM and drought stress [31]. Crop residue-based MBC also adds essential nutrients to soils, further supporting plant growth and stress resilience.

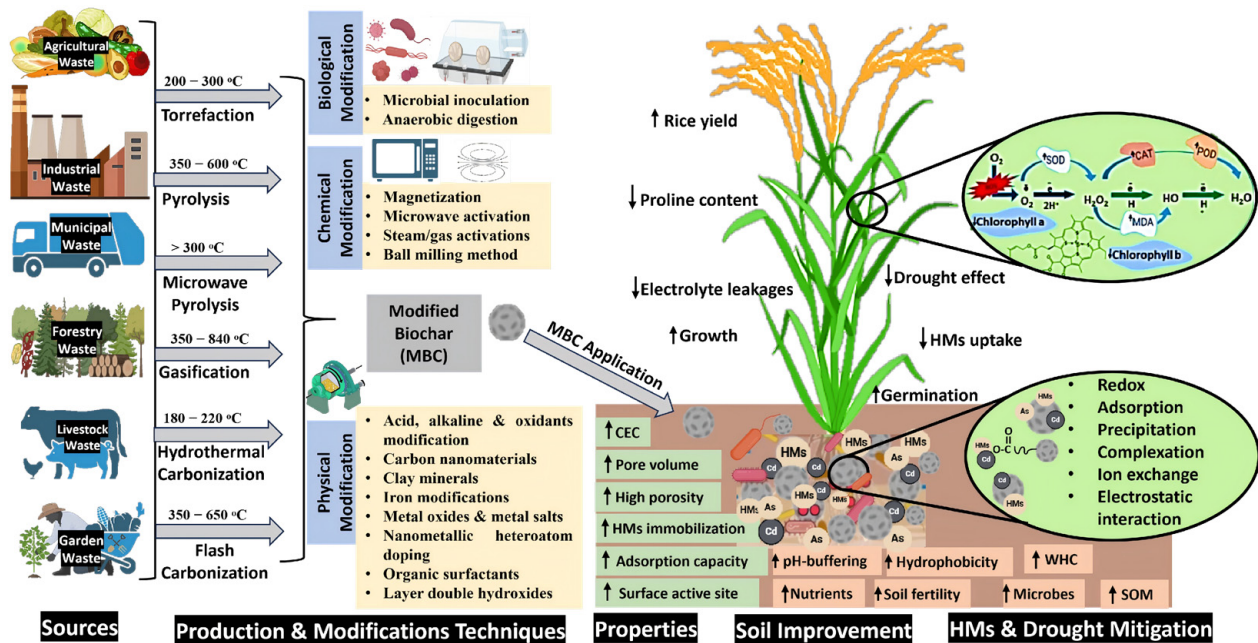


Figure 3. Different sources and methods of MBC preparation and its role in HMs and drought in rice.

MBC derived from animal manure, such as poultry litter and dairy manure, undergoes modifications to increase its nutrient release and adsorption capacities. These MBCs are rich in P and N, providing essential nutrients for crops while binding heavy metals through chemical adsorption and precipitation mechanisms [45]. Modified manure-derived BC also supports beneficial microbial communities, enhancing soil health and plant stress tolerance in challenging conditions [79]. Municipal solid waste (MSW) and sewage sludge are increasingly used as feedstocks for MBC, although they require careful processing to minimize contaminants. Modified MSW-based BC exhibits excellent adsorption capacities for HMs, reducing their mobility and bioavailability in soils [80]. Moreover, sewage sludge-derived MBC, after treatment to remove possible pathogens and pollutants, provides a sustainable option for remediating metal-contaminated soils and enhancing soil fertility.

Renewable feedstocks such as algal biomass and aquatic plants, like water hyacinth, are gaining attention for MBC production. Modifications enhance their metal adsorption properties, making them effective for cleaning aquatic systems impacted by HMs and producing MBC suitable for agricultural applications [81]. These feedstocks also contribute to the circular economy by utilizing invasive species and waste biomass for sustainable purposes. Energy crops like switchgrass and miscanthus, grown specifically for biochar production, are sustainable feedstock options. After modification, biochar derived from these crops demonstrates a high CEC and water-holding capacity, improving soil resilience in drought-prone areas [82]. These crops also grow well in nutrient-poor soils, contributing to land rehabilitation and sustainable BC production. The selection of feedstock and modification strategy for MBC production should align with the specific remediation needs for HMs and drought stress. Considerations such as local agricultural practices, biomass availability, and environmental sustainability are critical for maximizing the benefits of MBC in rice cultivation.

3.2. Properties of Modified Biochar

MBC is increasingly recognized as a superior soil amendment compared to traditional BC due to its enhanced capabilities in reducing the bioavailability of toxic heavy metals and improving water retention under drought stress (Figure 3). Recent research, such as studies by Huang et al. [83] and Yang et al. [45], has shown that MBC undergoes chemical

modifications, often including mineral loading or surface oxidation, which introduce more active functional groups like carboxyl and hydroxyl. These groups interact more effectively with metal ions like Cd and As, creating stable complexes that limit the metals' mobility in the soil and reduce their uptake by rice plants. For instance, in a study by [31], MBC was found to decrease Cd and As bioavailability by over 56% and 46%, respectively, significantly reducing the metal's concentration in rice grains and thereby enhancing food safety. This adsorption process is also aided by MBC ability to buffer soil pH, transforming metals into less soluble forms. This buffering effect is particularly beneficial in acidic soils, where metals are otherwise more bioavailable and toxic to plants.

In drought conditions, MBC offers significant advantages over simple BC by maintaining higher soil moisture levels through improved porosity and hydrophilicity. A study by Wen et al. [34] demonstrated that MBC produced 32% more grain yield under alternately wet and dry irrigation as compared to the control, a property that allows rice plants to access moisture for longer periods during drought spells. This moisture retention also supports beneficial microbial activity, which further enhances nutrient cycling and root growth, as observed by [76]. The enriched surface area of MBC and its enhanced CEC enable it to hold onto vital nutrients like potassium, magnesium, and calcium, which are essential for drought resilience. These nutrients are gradually released to rice plants, mitigating the adverse effects of nutrient leaching common under water-scarce conditions [32]. Moreover, the presence of specific mineral coatings, as explored in studies by [84], provides MBC with additional adsorptive sites, which are particularly effective in binding with heavy metals and reducing oxidative stress in rice plants—a critical factor in sustaining plant health under combined drought and heavy metal stresses.

The dual role of MBC in addressing both drought and heavy metal contamination makes it a practical sustainable solution for rice farmers facing climate and soil challenges. By reducing toxic metal uptake and supporting moisture retention, MBC improves overall plant health, enhances grain quality, and ensures more stable yields. Studies such as those by Sharma et al. [62] and Chen et al. [36] highlight that the application of MBC in contaminated fields led to significant increases in rice yield and quality under both heavy metal stress and drought. These findings underscore the importance of MBC as a tool not only for improving rice production but also for safeguarding food security and supporting the sustainability of agricultural practices in regions affected by soil contamination and climate variability. The continued development and field trials of MBC, focusing on optimal modification techniques and application rates, are critical for maximizing its efficacy in diverse agricultural systems.

3.3. Various Application Methods of MBC

MBC application methods are pivotal in mitigating the combined stresses of HMs and drought in rice cultivation. These methods leverage MBC-enhanced properties to improve soil structure, retain moisture, and immobilize HMs, thereby bolstering crop resilience and productivity. Incorporating MBC into the soil is a common method, involving its distribution over the field, followed by tilling. Optimal application rates range from 5 to 20 tons per hectare, effectively enhancing soil moisture retention and nutrient availability while reducing HM bioavailability through adsorption and precipitation mechanisms [74]. The high surface area of MBC provides abundant binding sites for Cd and As ions, preventing their uptake by rice roots [31]. This method also reduces water evaporation, improves root zone aeration, and stabilizes metals, making it highly effective in field conditions [38]. In greenhouse and pot experiments, MBC is typically applied in smaller doses, such as 2–10% by soil weight, to study its effects on HM stabilization and drought tolerance in rice plants. Research indicates that MBC-amended soils in greenhouse trials significantly im-

prove plant water use efficiency and reduce metal toxicity through complexation reactions with functional groups on the MBC surface, such as carboxyl and hydroxyl groups [34,69]. These controlled applications are essential for optimizing MBC rates and understanding mechanisms before large-scale field implementation [65].

Surface broadcasting involves spreading MBC across the field using equipment like lime or compost spreaders, often followed by light tilling to minimize wind loss. This method ensures uniform distribution and is suitable for large-scale applications [76]. MBC may also be applied in liquid form, where micronized MBC particles are injected directly into the soil root zone via fertigation. For instance, combining MBC with liquid manure at 1–5% increases nutrient availability, alleviates drought stress, and decreases HM mobility in soil [35]. This method is effective in no-till and irrigated systems where soil disturbance must be minimized, providing direct MBC benefits to the root zone [85]. Each application method should be tailored to specific soil types, climatic conditions, and crop requirements to maximize the benefits of MBC in mitigating HMs and drought stress in rice cultivation.

3.4. Potential Mechanisms by Which BC Improves WUE and Drought Effect

BC has been widely recognized for its ability to enhance WUE and mitigate drought stress in plants. Table 4 summarizes findings from previous meta-analyses, highlighting the mechanisms through which BC improves WUE and alleviates drought effects. BC enhances soil water retention due to its porous structure, which increases the soil's water-holding capacity and ensures moisture availability during dry periods. For example, sandy soils treated with BC showed a 28.5% increase in available water content (AWC), significantly improving WUE [86]. Similarly, coarse-textured soils, which inherently have low water retention, demonstrated a 45% increase in AWC following BC application [87]. BC also improves nutrient retention and availability, particularly in soils with high porosity and a small particle size. Its enhanced CEC facilitates better nutrient retention, thereby improving plant performance under water-deficient conditions [88]. For instance, fine-textured soils amended with BC showed a 23.8% increase in plant water use efficiency (PWUE), particularly in soils with a pH > 8 [89].

In addition to its effects on soil properties, BC fosters a favorable environment for beneficial microorganisms. These microorganisms play a critical role in nutrient cycling and support drought resilience by improving root function and water uptake. Such benefits are especially evident in soils with a low carbon content and high bulk density, where BC significantly enhances WUE [90]. BC also helps alleviate hydrological constraints in sandy and clayey soils by reducing salinity and bulk density. Its specific properties, such as high surface area and porosity, enhance water retention across soil types. For instance, coarse-textured soils showed a 25.6% increase in AWC with BC application [91]. These findings underscore the ability of BC as a sustainable amendment to optimize WUE and enhance plant resilience under drought conditions. By improving soil structure, nutrient dynamics, and microbial activity, BC offers a proficient solution to boost agricultural productivity in water-scarce regions.

Table 4. Different meta-analysis studies about BC applications improving the soil and plant water use efficiency.

Sr.	Observation	Soil Type	AWC	WUE	Comments	Reference
1	681		26.8%	4.7–15.2%	Woody BC has higher benefits than crop residue BC on WUE.	[90]
2	176 (82)	Coarse textured	45%		BC has greater benefit on coarse-textured soils.	[87]
3	176 (82)	Medium textured	21%			
4	176 (82)	Fine textured	14%			
5	284 (43)	Fine textured		23.8%	Greatest increases in PWUE was found in soils with pH > 8.	[89]
6	284 (43)	Medium textured		17.6%		
7	284 (43)	Coarse textured		19.4%		
8	(37)		25.5%		To achieve optimum water relations in sandy and clayey soils, biochar with a small particle size and high specific surface area and porosity should be applied.	[88]
9	121 (22)	Sandy soil	28.5%		BC has the possibility to alleviate the hydrological constraints of sandy soils, leading to more drought-resistant soils in the face of an expected dryer climate.	[86]
10	381 (63)			14.28%	BC with less carbon content in the soil with a large bulk density and low nutrients could better achieve a win–win situation in crop productivity and resource use efficiency.	[92]
11	939	Coarse textured	25.6%		Specific properties of BC are important factors affecting the water retention of soils with different textures. Differences in soil texture cause heterogeneity in the mechanisms by which BC improves soil water retention.	[91]
12	939	Medium textured	20.9%			
13	939	Fine textured	11.5%			

3.5. Potential Mechanisms by Which MBC Mitigates Drought Stress

MBC reduces drought stress in rice through a series of specialized mechanisms that extend beyond those offered by simple BC. These mechanisms can be grouped into three main categories: moisture retention, nutrient stabilization, and biological support, all of which contribute to enhanced drought resilience and WUE in rice plants and soil [33]. The enhanced porosity of MBC, achieved through structural modifications, allows it to retain more water than BC, acting as a reservoir that gradually releases moisture to rice plants during drought periods [34]. Studies have shown that the increased surface area and microporosity created during MBC production and treatment processes significantly increase its water-holding capacity, reducing the frequency and intensity of drought stress. These modifications allow MBC to trap water molecules within its structure, minimizing

evaporation and creating a stable microclimate around the root zone [87,93]. By retaining moisture and making it available to rice plants over extended periods, MBC helps to buffer plants from short-term fluctuations in soil moisture, allowing rice crops to maintain growth rates even under water-limited conditions [94]. Further, MBC enhances soil aggregation and reduces compaction, which improves aeration and promotes root penetration into deeper soil layers (Table 5). This deeper root development is essential for drought resistance, as it enables rice plants to access moisture from lower soil profiles that retain water longer during dry periods [85,95]. Furthermore, the mineral additives often used in MBC provide additional physical stability to soil aggregates, maintaining soil porosity and ensuring better root-to-soil contact. This structural improvement supports water infiltration and retention in the soil, making it available to rice roots over time, which enhances the plant's drought resilience [93,96].

One of MBC's critical chemical advantages is its enhanced CEC, which enables it to retain essential nutrients like K, Mg, and Ca in the soil matrix. These nutrients are crucial for rice plants, particularly under drought stress, as they regulate water uptake, osmoregulation, and metabolic processes related to drought adaptation [32]. Unlike simple BC, which has a limited CEC, MBC surface modifications create more reactive sites for nutrient binding. This capacity to hold and gradually release nutrients prevents leaching and ensures that rice plants have access to necessary minerals even in drought conditions [97]. By reducing nutrient leaching, MBC maintains soil fertility, allowing rice plants to sustain growth and improve yield stability during water shortages [98]. Moreover, MBC porous structure and mineral-enriched surfaces create favorable habitats for beneficial microorganisms, such as rhizobacteria and mycorrhizal fungi, which play a vital role in drought stress alleviation. These microbes assist in nutrient cycling and support the bioavailability of nutrients critical for rice growth. They also contribute to the breakdown of organic matter, gradually releasing nutrients in a manner that aligns with the plant's needs under stress [79]. The presence of a robust microbial community around the rice root zone also helps to stimulate root growth and nutrient uptake, further enhancing drought resilience. By fostering symbiotic relationships with roots, these microbes enable rice plants to optimize water and nutrient absorption, contributing to improved drought tolerance [76].

MBC's pH-buffering capacity is another mechanism that aids in drought mitigation (Table 5). Drought conditions often lead to soil acidification or salinity buildup, both of which limit nutrient availability and increase stress on rice plants [51]. The modified surface of MBC neutralizes soil pH, reducing the solubility of toxic ions and creating a more favorable environment for nutrient uptake [94]. Additionally, by binding with salt ions, MBC mitigates osmotic stress on rice roots caused by high salinity, which is a common issue in drought-affected soils. This ion-binding property prevents salt accumulation in the root zone, reducing salt stress and allowing rice plants to continue normal growth functions even under water-limited conditions. Further, the improved moisture retention and gradual release by MBC help stabilize the soil microclimate, preventing extreme temperature fluctuations that often accompany drought. This stable microclimate around the rice roots reduces transpiration rates and conserves plant energy, allowing for better drought endurance [56]. By limiting daily moisture loss, MBC maintains soil moisture levels for extended periods, creating a more resilient soil environment that enables rice plants to cope better with prolonged drought periods [89]. In short, these mechanisms combined make MBC a powerful tool for mitigating drought stress in rice cultivation, providing not only enhanced moisture retention but also a suite of chemical and biological benefits that together ensure better water and nutrient management in challenging growing conditions.

In addition to an increased physical water-holding capacity, drought resistance in rice plants is improved via some other biochemical and biophysical processes mediated by MBC treatments [97]. As regards biochemical mechanisms, MBC soil amendments increase the content of osmolytes such as proline, glycine betaine, and soluble sugars, ensuring cellular osmotic pressure and protein structure stabilization under drought conditions [97]. The application of biochar is associated with increased activities of several antioxidant enzymes, namely, SOD, CAT, and APX, preventing ROS build-up and oxidative damage to cell membranes. Furthermore, MBC treatments change the hormonal response of rice to drought, lowering the level of abscisic acid and ensuring its necessary concentration for stomatal regulation. Biophysical changes related to MBC treatments include enhanced soil aggregation characterized by mean weight diameter increases, thus decreasing crust formation and water evaporation [99].

Table 5. Feedstock, preparation method, and role of modified biochar against HMs and drought.

Biochar	Feedstock	Modifier	Method	Dose	Stress	Experiment	Improvement Effect	Reference
Fe-Mn oxide-modified biochar	Rice straw	Fe(NO ₃) ₃ and KMnO ₄	Muffle furnace at 300 °C for 4 h	0.5, 1.0, 2.0, and 4.0 g/kg	Cd in soil and rice	Rice, pot experiment, 2021	Significantly increased the biomass of brown rice (26.8%), and increased the removal efficiencies of CaCl ₂ extractable Cd in soil and Cd in pore water	[100]
Acid- and base-modified biochar	Sheep manure and rice husk residues	Sodium hydroxide, nitric acid	Slow pyrolysis, 500 °C for 4 h	2% (<i>w/w</i>)	Cd	Soil incubation (90 days)	reducing water soluble and exchangeable Cd fractions (−20.5%).	[101]
ZnO and MnO ₂ NP-modified BC	Wheat straw	KMnO ₄ and zinc oxide nanoparticles	Pyrolyzed for 3 h at 500 °C	0.5%, 1.0%	Pb, Cd, Zn, and Ni	Ryegrass, pot experiment	Increased shoots and roots dry weight of ryegrass. HMs uptake by ryegrass roots and shoots decreased significantly	[102]
Mn-modified tobacco rod, rubber, and coconut shell BC	Tobacco rod BC, rubber BC, and coconut shell BC	MnCl ₂ solution	Muffle furnace at 500 °C for 30 min	1, 3, and 5%	Pb, As, Cd, Cu, and Zn	Soil experiment	Mn-modified biochar could effectively improve soil physicochemical properties and significantly increase soil nutrient activity	[103]

Table 5. Cont.

Biochar	Feedstock	Modifier	Method	Dose	Stress	Experiment	Improvement Effect	Reference
Fe-Mn-modified biochar	Rice stalks and reeds	Ferromanganese slag	Pyrolyzed and carbonized	15 t/ha	Cd	Rice, field experiment	Decreased the content of cadmium in roots, stems and leaves of rice at the peak tillering stage by 17.24–49.28% in comparison to the control	[95]
Phosphoric acid-modified biochar	Wheat straw	H ₃ PO ₄ solution	Pyrolyzing at 500 °C for 4 h	10%	Heavy metals	Swine manure composting	BC and BP decreased Cu and Zn by 12.04%, 15.15% and 26.91%, 36.50%, respectively. Furthermore, reduced the total abundances of nine ARGs by 4.02% and 66.21%, and five MRGs by 53.66% and 58.81%, compared to CK in the compost product.	[104]
Ferromanganese oxide biochar	Corn straw	KMnO ₄ , Fe(NO ₃) ₃	Pyrolysis, 600 °C, 8 h	2.5% in pot, 1 ton/ha in field	Cd	Rice, soil incubation and field experiment	Increased the maximum sorption capacity of Cd on FMBC (50.46 mg/g) due to increased surface area. Reduced the Cd concentration in roots, shoots and grains by 37.97%, 33.98%, and 53.66%, respectively.	[93]
Hematite-modified biochar, KMnO ₄ -activated biochar	Corn straw	KMnO ₄ , hematite	Pyrolyzing, 500 °C, co-precipitated	2% w/w	Soil Cd and Zn	Foxtail millet pot experiment	reduced the phytotoxicity of bioavailable acid-soluble Cd and Zn were reduced by 57.79% and 35.64%, respectively. Chlorophyll, total protein contents and the SOD activity was enhanced.	[105]

Table 5. Cont.

Biochar	Feedstock	Modifier	Method	Dose	Stress	Experiment	Improvement Effect	Reference
Iron (Fe)-modified biochar (FeBC)	Platanus orientalis Linn (Oriental plane) branches	FeCl ₃	Pyrolyzed 650 °C, 1 h–2 h	3%, w/w	As, Cd, Pb stress	Rice pot experiment	FeBC increased the grain yield by 60% and 32% in continuously flooded or alternately wet and dry irrigation treatments. FeBC can be recommended for immobilization of As in paddy soils.	[34]
Fe-modified biochar	Rice straw	FeCl ₃	Pyrolyzed at 600 °C for 4 h	8.0 Mg ha ^{−1}	Soil aggregates	Rice field experiment	Fe-modified biochar is a better organic amendment to improve the stability of aggregates structure, SOC and enzymatic activity in saline–alkaline paddy soil	[66]
Biochar-embedded slow-release nitrogen	Acacia (Acacia nilotica) wood	Urea and NH ₄ Cl	450 °C for 6 h in a pilot-scale slow pyrolysis	68.9 mg in 0.8 kg soil	NUE, growth and rice yield	Incubation experiment, rice field experiment	Improved plant growth to increase grain yield (6610 kg ha ^{−1}), straw yield (9612 kg ha ^{−1}) and NUE (12%) in rice.	[98]
Silica-modified biochar (SBC)	Poultry manure	Si in the form of K ₂ SiO ₃ ·2.5H ₂ O	Pyrolysis at 450 °C for 3 h	0%, 1%, and 3% w/w	Drought and salt stress	Pot experiment	SBC displayed substantial capability in reducing soil salinity and drought stress and improved nutrient availability and plant uptake.	[94]

3.6. Potential Mechanisms by Which BC Mitigates HMs

BC is an effective soil amendment for mitigating the synergistic impacts of HMs and drought stress in rice cultivation. The porous structure of BC enables it to act as a water reservoir, retaining moisture and gradually releasing it to plants during periods of drought (Table 6). This property helps maintain soil hydration, even in drought-prone environments, supporting rice plant resilience by reducing the frequency and severity of water stress. At the same time, BCs' high surface area and abundant functional groups bind with HM ions, immobilizing them and reducing their bioavailability. This prevents

heavy metals from being absorbed by rice roots, which is crucial for food safety and plant health. BC also buffers soil pH, particularly beneficial in acidic soils where HMs are more soluble and toxic. By neutralizing soil acidity, BC helps transform metals into less soluble forms, thus limiting metal toxicity and promoting nutrient uptake essential for rice growth [37,96]. Additionally, BC supports beneficial microbial communities that assist in the breakdown and transformation of HMs into less toxic species, while these microbes also play a role in nutrient cycling, enhancing water use efficiency and plant growth under drought conditions. In terms of chemical interactions, BC forms stable complexes with HMs through ion exchange, adsorption, and precipitation mechanisms. For instance, Cd^{2+} ions bind with oxygen-containing groups on the BC surface, while As precipitates as metal arsenates, reducing its bioavailability to plants. Furthermore, BC reduces water loss by evaporation and fosters root growth, allowing plants to access deeper water reserves in the soil, which is particularly beneficial under combined HM and drought stress [64]. This dual mitigation strategy, addressing both HMs and drought, underlines BC's role in promoting sustainable, resilient rice production in contaminated and water-limited environments.

Table 6. BC improves rice growth and yield by mitigating the HMs and drought stress.

Stress	BC Source	Pyrolysis °C	Application Rate	Soil Type	Exp. Type	Effect	References
Cd, Cu, and water regimes	Rice straw	700	20, 40, 60 g/kg	Sandy loam	Pot	HMs reduce in brown rice; Cd 51–81.5%, and Cu 31–74%	[36]
Cd, Cu, and water regimes	Rice husk and straw	700, 2 h	20, 50 g/kg	Sandy loam	Pot	HMs reduce in rice; Cd 6.8–20.0%, and Cu 5.6–18.2%	[37]
Cd and drought	Rice straw	450, 2 h	3, 5% <i>w/w</i>	Clay loam	Pot	5% BC reduces Cd and increases rice yield in drought stress	[38]
Heavy metal	Bean stalk and rice stalk	500, 8 h	20 tons ha^{-1}	Wastewater 50 Years	Field	Cd and Fe concentrations reduce in root, shoot and rice grain by 26–81%	[40]
Cd, Pb	Wheat straw	350–550	10, 20, 40 t ha^{-1}	Hydroagric stagnic anthrosol	Field	BC increases soil pH and TOC and decreases Cd and Pb contents in rice plant	[39]
PTEs, Cd	Sewage sludge	500, 3 h	1.5, 3.0 t/ha	PTEs with Cd-contaminated soil	Field	Increases grain yield by 1.9–3.4 g/plant, reduces PTEs and Cd	[41]
Pb, Cd	Wheat straw	350–550	10, 20, 40 t/ha	Anthrosol	Field	Enhances grain yield, reducing Pb, Cd, GHG and carbon emissions	[42]
Cd	Wheat straw	485	20, 40 t/ha	HM-contaminated	Field	Enhances grain yield and soil pH, reducing Cd in rice grain, root, and shoot by 20–85%	[43]

Table 6. Cont.

Stress	BC Source	Pyrolysis °C	Application Rate	Soil Type	Exp. Type	Effect	References
Cd, Pb	Dead pig + Fe	Pig BC 650, 2 h, Pig BC + Fe 650, 1 h	15.6, 39, 78 t/ha (1, 2.5, 5%)	Paddy soil	Pot	Enhances pH and decreases Cd by 43–59% and Pb by 55–82% in paddy soil	[45]
As	Dead pig	650, 2 h	15.6, 39, 78 t/ha (1, 2.5, 5%)	Paddy soil	Pot	Enhances pH and decreases As by 35.4–38.7% in paddy soil	[44,106]
Drought	Rice straw	600	20, 30, 40, 50% w/w		Field	Enhances yield and reduces drought effect in direct seeded rice	[56]

3.7. Potential Mechanisms by Which MBC Mitigates HMs

MBC is more effective than unmodified BC in mitigating HM contamination in rice cultivation due to its enhanced physicochemical properties, which promote HM immobilization and detoxification more effectively than standard biochar (Figure 3). The surface modifications of MBC, such as mineral loading or functional group enhancements, provide a greater number and variety of binding sites for metal ions like Cd and As, thus reducing their bioavailability in soil and minimizing their uptake by rice plants [77]. Studies by Ahmad et al. [94] and Chen et al. [104] demonstrate that the MBC-increased surface area and porous structure offer extensive sites for binding and stabilizing HM ions. Through complexation and adsorption processes, heavy metals adhere strongly to the MBC surface, where they undergo interactions with functional groups such as hydroxyl, carboxyl, and phenolic groups. For example, Cd²⁺ ions bind with these oxygen-containing groups to form stable, non-soluble complexes, which effectively restrict metal ions from reaching plant root zones [45,95].

Beyond direct adsorption, MBC plays a crucial role in altering soil chemistry to further immobilize heavy metals. Its pH-buffering capability is especially beneficial in acidic soils, where HMs are typically more soluble and toxic to plants. By stabilizing or slightly raising soil pH, MBC transforms metals like Cd and As into less soluble forms, thereby reducing their mobility and uptake by plants [101,107]. For instance, As is converted to less bioavailable arsenate forms under neutral to alkaline conditions induced by MBC, which not only diminishes As toxicity but also promotes a healthier nutrient balance in the soil. These pH alterations provide a supportive environment for rice plant growth under HM stress and ensure that essential nutrients remain accessible to plants [34].

Additionally, MBC fosters an environment conducive to beneficial microbial activity, which plays a vital role in HM detoxification. The porous and mineral-rich structure of MBC creates ideal habitats for metal-tolerant soil microorganisms, including those that facilitate biosorption and redox transformations, further stabilizing heavy metals within the soil matrix. These microbial processes reduce metals to less toxic states, effectively diminishing their bioavailability and limiting their potential to leach into groundwater, thus protecting surrounding ecosystems [79]. Research confirms the efficacy of MBC in significantly reducing concentrations of Cd and As in rice grains, a critical outcome for food safety in regions facing HM contamination. The combined effects of MBC—enhanced adsorption, pH regulation, and microbial support—create a comprehensive remediation strategy, making MBC a potent and sustainable tool for rice production in contaminated

areas [31,105]. By immobilizing heavy metals and enhancing soil resilience, MBC supports sustainable agricultural practices aimed at minimizing environmental contamination and protecting human health [83,85].

4. Future Directions and Challenges

4.1. Contradictory Findings

Despite these beneficial effects of modified biochar, several studies have reported some contradictory findings regarding their contextual limits. The introduction of biochar in paddy soils results in enhanced mobilization of arsenic, especially during the first phase of cultivation, because dissolved organic matter produced from biochar forms complexes with As while facilitating the reductive dissolution of iron oxides [108]. On the contrary, according to Tang et al. [109], bamboo biochar decreased the availability of arsenic by forming stable As-Fe-DOM ternary complexes in the paddy soil. Similarly, biochar works effectively for cadmium immobilization under acidic soil, but it shows negative impacts when used in alkaline soil because biochar increases the loss of cadmium through leaching [110]. The effectiveness of MBC varies significantly depending on environmental and site-specific factors such as soil type, crop species, and local climate. For example, MBC modified with iron oxides performs well in acidic soils with high cadmium contamination but has limited effects in neutral or alkaline soils. Similarly, while MBC is highly effective in sandy soils for enhancing moisture retention, its impact may be less pronounced in clay-rich soils where water retention is inherently higher. Such variability in performance across different agricultural conditions makes it challenging to develop a universal application strategy, leading to inconsistent results in diverse farming systems [100,111].

4.2. Identify Research Gaps and Areas for Future Investigation

This review underscores the critical need for future investigations into the long-term impacts of BC and MBC on soil health, crop resilience, and agricultural sustainability. However, research is also urgently needed on real-time biochemical effects, such as oxidative stress, which can be assessed without long-term longitudinal studies. While the short-term benefits of MBC—such as enhancing soil fertility, reducing heavy metal toxicity, and improving drought tolerance—are well-documented, gaps remain in understanding its prolonged effects. For instance, MBC interactions with soil properties over extended periods could lead to changes in pH, microbial diversity, and nutrient cycling, which influence rice yield and quality in unanticipated ways. Research on the sustainability of MBC under various soil conditions, particularly in continuous rice farming systems, is essential. Continuous application produces cumulative effects on the soil ecosystem, necessitating studies that assess how these changes evolve over time and their implications for productivity and environmental health [110,112]. Further exploration is needed to understand how MBC addresses multiple agricultural challenges through integrated approaches. For instance, combining MBC with organic fertilizers, crop rotation, or phytoremediation practices offer synergistic benefits, addressing not only heavy metal contamination and drought stress but also broader issues like soil degradation [30]. Investigating these combinations could pave the way for more holistic strategies to enhance rice productivity sustainably.

Additionally, the interaction of MBC with various rice cultivars and environmental conditions, such as climate zones, soil types, and seasonal rainfall variability, remains underexplored. These factors significantly influence MBC efficiency, requiring site-specific studies to optimize its use across diverse agricultural systems [113,114]. The economic and practical barriers to MBC adoption are another critical area for future research. While the benefits of MBC are evident, its widespread implementation in rice farming, especially in developing regions, is hindered by high production costs, limited scalability, and logistical

challenges. Comprehensive economic feasibility studies are required to evaluate the cost-effectiveness of MBC production and application at a larger scale. Addressing questions of scalability, especially for smallholder farmers, is vital to ensure MBC adoption as a practical solution [115]. Moreover, policy frameworks and farmer education programs must be developed to encourage the use of MBC. Without adequate institutional support and training, adoption rates might remain low, particularly in regions where farmers face concurrent economic and environmental pressures [34,79].

The potential human health implications of MBC-treated rice also require thorough investigation. While MBC reduces the bioavailability of harmful metals like cadmium and arsenic in rice grains, there is a need to ensure that MBC itself does not introduce new risks, such as residues or contaminants entering the food chain. Over-application of MBC or the use of low-quality, poorly processed feedstocks could theoretically release harmful compounds into the soil or crops. Research into food safety, including the risk of unintended contamination, is essential to building confidence in MBC as a safe agricultural amendment [116,117]. Finally, advancing MBC as a sustainable and scalable solution will require a deeper understanding of its synergistic effects when combined with other drought-resistant strategies and soil improvement techniques. Studies focusing on MBC's long-term environmental impacts, such as its contribution to carbon sequestration and resilience against soil erosion, are crucial to evaluating its role in sustainable agriculture. By addressing these research gaps, MBC could be further developed into a transformative tool for mitigating heavy metal contamination and drought stress, while promoting the sustainable intensification of rice cultivation systems. Its integration into comprehensive soil and crop management practices has the capacity to enhance agricultural productivity and environmental sustainability in the face of growing global challenges [77,94].

4.3. Practical Limitations and Negative Effects of MBC Applications

MBC, despite its promise as an agricultural amendment, faces several limitations that challenge its widespread adoption, particularly in resource-limited and smallholder farming systems. One significant constraint is the high application rate often required to achieve tangible improvements in soil health and HM immobilization. While unmodified biochar typically demands 5–20 tons per hectare for observable benefits, MBC allows for reduced dosages due to its enhanced adsorption properties and tailored functionalities. However, even with reduced application rates, the cost of producing, transporting, and applying MBC remains a substantial barrier for smallholder farmers, as the materials and processes required for its modification—such as chemical activation or nanoparticle incorporation—are often expensive and resource-intensive [35,76]. Logistical challenges compound these issues. Even if MBC is commercially available, its bulkiness and weight can make transport to remote or fragmented farming areas costly and labor-intensive. Additionally, uniform field application of MBC remains a logistical hurdle, as uneven distribution can lead to inconsistent results. For smallholder farmers, who often lack access to mechanized tools for application, the labor-intensive process of incorporating MBC into the soil can be prohibitive [76,113].

Another limitation is the delayed onset of benefits associated with MBC use. Improvements in soil structure, heavy metal stabilization, and nutrient retention often develop gradually, requiring several growing seasons before measurable impacts on crop yields or soil health are evident. For farmers seeking immediate solutions to improve soil fertility or mitigate contamination, this delay can be a deterrent. The slow response time of MBC contrasts with chemical fertilizers, which deliver quicker, albeit less sustainable, results [118]. Moreover, the BC soluble organic matter also causes injury to earthworms' intestinal epithelial cells and gut microbial community [119]. Nano BC is highly toxic to

bacteria as compared to BC (18–2886%) [120]. Collectively, these factors highlight the limitations of MBC as a large-scale amendment, particularly in resource-constrained agricultural systems. Addressing these challenges requires targeted solutions such as the development of low-cost modification methods, improved access to pre-modified biochar, and tailored application strategies suited to specific soil and crop conditions. By addressing these barriers, the broader adoption of MBC could become more feasible, enabling its benefits to be realized more effectively across diverse farming landscapes [94,113].

4.4. Potential Strategies to Overcome These Challenges

Optimizing MBC efficacy to mitigate HM contamination and drought stress in rice cultivation necessitates a multifaceted approach. The type of feedstock and modification techniques play pivotal roles in enhancing MBC's physical and chemical properties, which determine its capacity for HM immobilization and moisture retention. Unlike unmodified biochar, MBC is engineered through methods such as chemical activation (e.g., impregnation with iron, magnesium, or calcium salts) or physical activation (e.g., steam or gas treatments) to improve surface functionality and adsorption potential. For instance, MBC modified with iron oxides demonstrates superior adsorption of heavy metals like cadmium and arsenic due to its increased functional groups and altered surface charge. Similarly, pyrolysis conducted at 500–700 °C, followed by acid or alkali activation, enhances the surface area and porosity of MBC, significantly improving its water retention capabilities and ability to immobilize HMs. These modifications make MBC a powerful tool for addressing site-specific agricultural challenges, such as HM contamination in rice paddies [68,94,101]. Field application strategies for MBC must also be optimized to balance cost-effectiveness with environmental benefits. While typical application rates range from 5 to 20 tons per hectare, blending MBC with compost or organic amendments reduces the required dosage without compromising its efficacy. Localized applications, such as incorporating MBC into trenches or furrows, enhance its integration into the soil, minimize erosion, and maximize its effectiveness in stabilizing HMs and improving drought resilience. Additionally, advanced formulations of MBC, such as slow-release amendments, extend its benefits over time, reducing both the application frequency and overall costs. Recent studies also emphasize the potential of MBC in fertigation systems, allowing for precise nutrient delivery while simultaneously addressing soil contamination and drought stress [30,76].

Soil characteristics, including pH, texture, and organic matter content, significantly influence MBC's performance. The pH-buffering capacity of MBC is particularly beneficial in acidic soils, where it decreases the solubility and bioavailability of HMs, improving overall soil health and crop productivity [101]. In sandy soils with low water-holding capacity, MBC-enhanced porosity and functional groups increase moisture retention, a critical factor for mitigating drought stress [94]. Additionally, modified biochar enriched with magnesium or iron oxides shows high specificity for adsorbing certain metals like cadmium and arsenic, further tailoring its application to specific soil conditions and contamination profiles [100,102]. Environmental factors such as weather and erosion potential also affect the retention and functionality of MBC in agricultural settings. Applying MBC during mild rainfall or incorporating it directly into the soil reduces wind and water erosion, particularly in sloped or erosion-prone areas. Using heavier or denser MBC particles further enhances retention in these environments [103]. Additionally, stabilizing agents such as gypsum or polymers can be co-applied with MBC to increase its durability and effectiveness under challenging field conditions [30]. Research highlights the potential of MBC nanocomposites for addressing both heavy metal immobilization and water retention challenges, showcasing its versatility in tackling agricultural and environmental stressors [96,104]. In a nutshell, optimizing MBC to mitigate HM contamination and drought stress in rice cultivation

requires a comprehensive approach that considers feedstock selection, modification techniques, application strategies, soil-specific characteristics, and environmental conditions. By integrating MBC with other amendments, leveraging slow-release formulations, and utilizing advanced modifications, it is possible to achieve significant improvements in soil health, crop resilience, and environmental sustainability. Customized MBC formulations and field application methods tailored to specific agricultural needs hold immense potential for enhancing the productivity and sustainability of rice cultivation systems [85,91,121].

5. Conclusions

This review paper has highlighted the significant challenges that heavy metals (particularly cadmium and arsenic) and drought pose to rice production, a crucial global staple. It has also demonstrated the potential of MBC as a recognized and multifaceted solution to mitigate these threats. MBC has been shown to reduce the bioavailability of toxic metals, improve soil fertility, enhance drought resistance, and contribute to more resilient agricultural practices. These benefits are crucial for maintaining food security, particularly in regions most affected by climate change and environmental degradation. However, while the potential of MBC is clear, further research is needed to better understand its long-term impacts on soil health, its interactions with other agricultural practices, and its economic feasibility for widespread adoption, especially in resource-limited settings. Future studies should focus on optimizing MBC's properties for specific environmental conditions, exploring its synergies with other mitigation strategies, and addressing its scalability and safety for both farmers and consumers. To unlock the full potential of MBC and ensure its sustainable implementation, it is vital that policymakers, researchers, and farmers collaborate to develop comprehensive, region-specific guidelines and support systems for its application. Ultimately, the integration of MBC into rice farming plays a key role in advancing sustainable agricultural practices that promote food security, environmental protection, and climate resilience for future generations.

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