

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Sustainable applications of rice feedstock in agro-environmental and construction sectors: A global perspective

Sabry M. Shaheen^{a,b,c}, Vasileios Antoniadis^d, Muhammad Shahid^e, Yi Yang^f,
Hamada Abdelrahman^g, Tao Zhang^h, Noha E.E. Hassan^{a,i}, Irshad Bibi^j, Nabeel Khan Niazi^j,
Sherif A. Younis^{k,l}, Mansour Almazroui^{m,n}, Yiu Fai Tsang^f, Ajit K. Sarmah^o, Ki-Hyun Kim^{k,**},
Jörg Rinklebe^{a,p,*}

^a University of Wuppertal, School of Architecture and Civil Engineering, Institute of Foundation Engineering, Water- and Waste-Management, Laboratory of Soil- and Groundwater-Management, Pauluskirchstraße 7, 42285, Wuppertal, Germany

^b King Abdulaziz University, Faculty of Meteorology, Environment, and Arid Land Agriculture, Department of Arid Land Agriculture, 21589, Jeddah, Saudi Arabia

^c University of Kafrelsheikh, Faculty of Agriculture, Department of Soil and Water Sciences, 33516, Kafr El-Sheikh, Egypt

^d Department of Agriculture Crop Production and Rural Environment, University of Thessaly, Greece

^e Department of Environmental Sciences, COMSATS University Islamabad, Vehari Campus, Vehari, Pakistan

^f Department of Science and Environmental Studies, The Education University of Hong Kong, Tai Po, New Territories, 999077, Hong Kong, China

^g Cairo University, Faculty of Agriculture, Soil Science Department, Giza, 12613, Egypt

^h Beijing Key Laboratory of Farmland Soil Pollution Prevention and Remediation, Key Laboratory of Plant-Soil Interactions of Ministry of Education, College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China

ⁱ Agricultural Extension and Rural Development Research Institute, Agricultural Researcher Center, Dokki, Giza, Egypt

^j Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, Faisalabad, 38040, Pakistan

^k Hanyang University, Department of Civil & Environmental Engineering, 222 Wangsimni-Ro, Seoul, 04763, Republic of Korea

^l Analysis and Evaluation Department, Egyptian Petroleum Research Institute, Nasr City, Cairo, 11727, Egypt

^m Center of Excellence for Climate Change Research (CECCR), Department of Meteorology, King Abdulaziz University, 21589, Jeddah, Saudi Arabia

ⁿ Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom

^o Department of Civil and Environmental Engineering, The Faculty of Engineering, The University of Auckland, Private Bag 92019, Auckland, 1142, New Zealand

^p Department of Environment, Energy and Geoinformatics, Sejong University, Seoul, 05006, Republic of Korea

ARTICLE INFO

Keywords:

Agricultural resources
Rice feedstock
Pyrolysis and composting
Contaminated soil and water
Sustainable management

ABSTRACT

Rice is second only to maize among the world's most important cereal crops, with a global harvested area of approximately 158 million hectares and an annual production of more than 700 million tonnes as paddy rice. At this scale, rice production generates vast amounts of waste in the form of straw, husk, and bran. Because of high cellulose, lignin, and silica contents, rice biowaste (RB) can be used to produce rice biochar (RBC) and rice compost (RC). Furthermore, RB can be used as sorbents, soil conditioners, bricks/concrete blocks, flat steel products, and biofuels, all of which make significant contributions to meeting United Nations Sustainable Development Goals (UNSDGs). Although previous reviews have explored individual applications of rice feedstocks, inadequate attention has been paid to multifunctional values and potential multi-utilities. Here, we offer a comprehensive review of RBC and RC with respect to: (1) preparation and characterization; (2) applications as soil conditioners and organic fertilizers and their effects on soil-carbon sequestration; (3) remediation of toxic element-contaminated soils and water; (4) removal of colors, dyes, endocrine-disrupting chemicals, personal-care products, and residual pesticides from water; and (5) applications in the construction industry. Specifically, we describe the opportunities for the sustainable use of RBC and RC in the management of contaminated soils and water as well as the construction industry. Overall, this review is expected to lengthen the list of possible multifunctional applications of RBC and RC.

* Corresponding author. University of Wuppertal, School of Architecture and Civil Engineering, Institute of Foundation Engineering, Water- and Waste-Management, Laboratory of Soil- and Groundwater-Management, Pauluskirchstraße 7, 42285, Wuppertal, Germany.

** Corresponding author.

E-mail addresses: Shaheen@uni-wuppertal.de (S.M. Shaheen), kkim61@nate.com (K.-H. Kim), rinklebe@uni-wuppertal.de (J. Rinklebe).

<https://doi.org/10.1016/j.rser.2021.111791>

Received 20 May 2021; Received in revised form 8 September 2021; Accepted 15 October 2021

Available online 22 October 2021

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1. Introduction

Among the world’s most important cereal crops, rice is second only to maize. Rice is consumed as a staple primarily in Asia and Africa. Approximately 162 million ha of land are devoted to rice cultivation, with more than 755 million tons of paddy rice produced annually, 496 million tons in the form of milled rice [1]. Asia alone accounts for 90% of the global rice supply [2]. China is the world’s largest paddy rice producer, with a production volume of more than 209 million tons in 2019 [2] (Table 1).

Rice waste is now a major concern in agricultural environments [3]. According to estimates by Balagurumurthy et al. [4], the rice paddy-to-straw ratio is 4.3:1, suggesting that a ton of paddy rice contains

233 kg of rice straw (RS). Approximately 163 million tons of RS is produced from 700 million tons of paddy rice annually. In an ideal and efficient milling process, the following fractions of rice are produced depending on the degree of milling: 68%–72% milled or white rice, 20% husk, and 8%–12% bran [5]. Based on a reference annual production of 755 million tons, the global annual production of rice husk (RH) is approximately 151 million tons (Table 1).

Every year, nearly 120 million tons of RH are produced and dumped as waste worldwide, while 8%–80% of paddy wastes are burned [3,6]. Currently, no sustainable solution is available to manage this volume of straw. As most farmers rely on in situ burning of straw, ecological, environmental, health, and economic issues are common in rice-dependent countries such as India and Egypt [7]. The inadequate disposal and open burning of rice waste can make a significant contribution to greenhouse-gas emissions (GHGs) [8]. For example, in Vietnam, Thailand, and the Philippines, approximately 23%, 48%, and 95%, respectively, of the aboveground straw biomass is subjected to open-field burning [9]. Open burning of straw is associated with widespread distribution of atmospheric pollutants such as hydrocarbons, creating negative impacts on regional climate trends and crop yields (Fig. 1) [10,11]. The generated waste is used as livestock feed, fuel, building materials, and compost [5,12,13]. Commercial application of the rice biowaste (RB) can therefore provide an alternative solution to the disposal issue.

In many industrial sectors, RH and husk ash are used to produce bricks and concrete blocks, flat steel, and biofuels [14,15]. They serve as raw materials for the production of industrial and laboratory chemicals, such as lignosulfonic acids, furfural, xylitol, acetic acid, and ethanol, and as polishing or cleaning agents in the machining and metal industries. Rice husks contain 75%–90% organic matter, such as lignin and cellulose [16]. They are composed of approximately 20% silica, 30% lignin,

Abbreviations	
RB	rice biowaste
RBC	rice biowaste-derived biochar
RC	rice biowaste-derived compost
C	biochar
RS	rice straw
RH	rice husk
RSBC	rice straw-derived biochar
RHBC	rice husk-derived biochar
RSC	rice straw-derived compost
RHC	rice husk-derived compost
TE	toxic element
SOM	soil organic matter

Table 1
Global rice waste generation and biochar yield and applicability to agricultural lands as a soil amendment.

Country	Total area (km ²)	Agricultural area (km ²)	Area under rice cultivation (km ²)	Rice production (tons)	Rice straw generated (tons)	Rice husk generated (tons)	Total waste generated (tons)	Biochar yield from waste (tons)	Agricultural area (km ²) available for biochar application
Global	510,072,000	134,000,000	1,620,600	755,473,800	175,691,581	151,094,760	326,786,341	163,393,171	163,393
China	9,597,000	1,400,000	308,711	209,600,000	48,744,186	41,920,000	90,664,186	45,332,093	45,332
India	3,287,000	1,597,000	441,000	117,650,000	27,360,465	23,530,000	50,890,465	25,445,233	25,445
Indonesia	1,905,000	570,000	115,000	54,600,000	12,697,674	10,920,000	23,617,674	11,808,837	11,809
Bangladesh	147,570	104,775	78,581	54,580,000	12,693,023	10,916,000	23,609,023	11,804,512	11,805
Vietnam	331,210	115,924	78,164.8	43,450,000	10,104,651	8,690,000	18,794,651	9,397,326	9397
Thailand	513,120	153,936	92,000	28,360,000	6,595,349	5,672,000	12,267,349	6,133,674	6134
Myanmar	676,575	118,700	67,900	26,270,000	6,109,302	5,254,000	1,1363,302	5,681,651	5682
Philippines	300,000	96,710	44,000	18,810,000	4,374,419	3,762,000	8,136,419	4,068,209	4068
Brazil	8,516,000	2,895,440	2,340,880	10,370,000	2,411,628	2,074,000	4,485,628	2,242,814	2243
Japan	377,915	49,000	15,750	10,530,000	2,448,837	2,106,000	4,554,837	2,277,419	2277
Pakistan	881,913	212,000	40,280	11,200,000	2,604,651	2,240,000	4,844,651	2,422,326	2422
Cambodia	181,035	56,121	30,520	10,890,000	2,532,558	2,178,000	4,710,558	2,355,279	2355
Egypt	1,010,000	30,240	4500	6,690,000	1,555,814	1,338,000	2,893,814	1,446,907	1447
Nepal	147,516	29,503	14,500	5,610,000	1,304,651	1,122,000	2,426,651	1,213,326	1213
South Korea	100,210	16,000	7550	5,020,000	1,167,442	1,004,000	2,171,442	1,085,721	1086
Sri Lanka	65,610	27,400	7080	4,590,000	1,067,442	918,000	1,985,442	992,721	993
Egypt	1,010,000	33,000	6500	6,690,000	1,555,814	1,338,000	2,893,814	1,446,907	1447
Tanzania	945,087	440,000	294,000	3,470,000	806,977	694,000	1,500,977	750,488	750
Madagascar	587,041	30,000	22,000	4,230,000	983,721	846,000	1,829,721	914,860	915
United States	9,834,000	3,631,649	11,493	8,380,000	1,948,837	1,676,000	3,624,837	1,812,419	1812
Malaysia	330,803	78,930	6897	1,880,000	437,209	376,000	813,209	406,605	407
Guinea	245,857	145,056	1240	2,599,000	604,419	519,800	1,124,219	562,109	562
Ghana	238,535	164,589	–	973,000	226,279	194,600	420,879	210,440	210
Afghanistan	652,237	378,754	2100	520,000	120,930	104,000	224,930	112,465	112
Bolivia	1,099,000	21,980	12,800	560,000	130,233	112,000	242,233	121,116	121
Benin	114,763	35,700	746	379,000	88,140	75,800	163,940	81,970	82
Bhutan	38,394	1124.9	273	88,000	20,465	17,600	38,065	19,033	19
Angola	1,247,000	54,700	–	15,556.69	3618	3111	6729	3365	3

Source: Shahbandeh [2] Principal rice-exporting countries worldwide in 2018–2019. Source: <https://www.statista.com/statistics/255947/top-rice-exporting-countries-worldwide-2011/>. 2021.

and 50% cellulose. Occasionally, RH is used as a source of silica for silica-rich products such as silicon chips [17].

Recently, researchers have focused on the production of compost and biochar (BC) from RH and straw because of their potential applications in environmental (Fig. 2) and agricultural (Fig. 3) sectors. For example, rice biowaste derived biochar (RBC) has been used widely in wastewater treatment [18,19], groundwater purification [20], dye removal [21,22], and toxic element (TE) sorption/immobilization [23–25]. Awareness of potential biochar application to soil has increased among farmers in recent years. The estimated global production of biochar reached nearly 353 tons in 2017, and was expected to increase by approximately 11.7% between 2019 and 2027 [26]. The importance of RBC in agriculture and its interaction with organic and inorganic pollutants in soil are summarized in Fig. 3.

The potential presented by RBC and rice compost (RC) for soil and water remediation has attracted a great deal of research interest (Fig. 4). A search of the Web of Science database using the key word “rice straw” resulted in more than 11,800 documents. From 2000 to 2021, more than 2300 and 1350 articles about RBC and RC, respectively, were published (Fig. 4). We compiled the key findings of a large number of studies on this topic to present a comprehensive picture of our scientific understanding of the subject.

Recycling of RB is important from agricultural and environmental points of view. The use of RBC by the construction industry has also drawn the attention of numerous researchers. This review is organized to provide updated information that will help research teams study RBC and RC. It was written to appeal to a wide range of stakeholders, including soil and water scientists, environmentalists, geologists, engineers, industrialists, and post-graduate students interested in improving the quality of environment.

In September 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs) and 169 targets, which all member states agreed to implement by 2030. These goals set out a vision of a world free from poverty, hunger, and disease. The topics of our article are designed to match eight of these goals: 1 (no poverty); 2 (zero hunger); 3 (good health and well-being); 6 (clean water and sanitation); 7 (affordable and clean energy); 9 (industry, innovation and infrastructure); 13 (climate action); and 15 (life on land).

Despite mounting evidence for individual functional applications of RBC, there is a general lack of understanding about the use of rice waste in environmental remediation programs and in the sustainable environment and construction industries. Several reviews have been published that cover individual functional applications of RBC and RC. However, little effort has been devoted to a comprehensive review of the multifunctional values and unintended consequences of both RBC and compost applications in the agro-environmental and construction sectors, particularly the achievements associated with meeting the SDGs.

To the best of our knowledge this paper is the first to emphasize critical aspects of this topic. It offers a comprehensive discussion of the potential utility of RBC and RC as soil conditioners; organic fertilizers; immobilizing agents for TEs in soils; sorbents for the removal of TEs, dyes, and residual pesticides from contaminated water; and (e) raw materials for the construction industry. We conduct a critically analysis of (i) preparation and characterization of RBC and RC; (ii) applicability of RBC and RC for improving soil properties, organic matter composition and fractions, carbon sequestration, soil fertility, and plant yields; (iii) remediation of TE-contaminated soils, (iv) removal of TEs, dyes, and residual pesticides in water, and (v) application of RBC in the construction industry.

2. Production of rice biowaste-derived biochar and compost

2.1. Rice biowaste-derived biochar

The direct combustion of rice waste with high ash content can cause fouling, slagging, and emissions of particulate matter [27]. It is often used to produce energy and heat. However, pyrolysis (chemical decomposition of organic materials at elevated temperatures in the absence of oxygen) of rice waste is a more promising approach to reducing emissions and obtaining a high-quality product in the form of BC. Biochar is a low-density, carbon-rich solid obtained from a variety of organic materials through pyrolysis in the absence, or under limited amounts of oxygen [26]. Biochar has proven to be a useful soil amendment due to its ability to remove toxic organic and inorganic pollutants [24,28]. Other uses include the prevention of fertilizer runoff and soil leaching as well as sustaining soil moisture.

The production of BC is strongly influenced by pyrolysis temperature

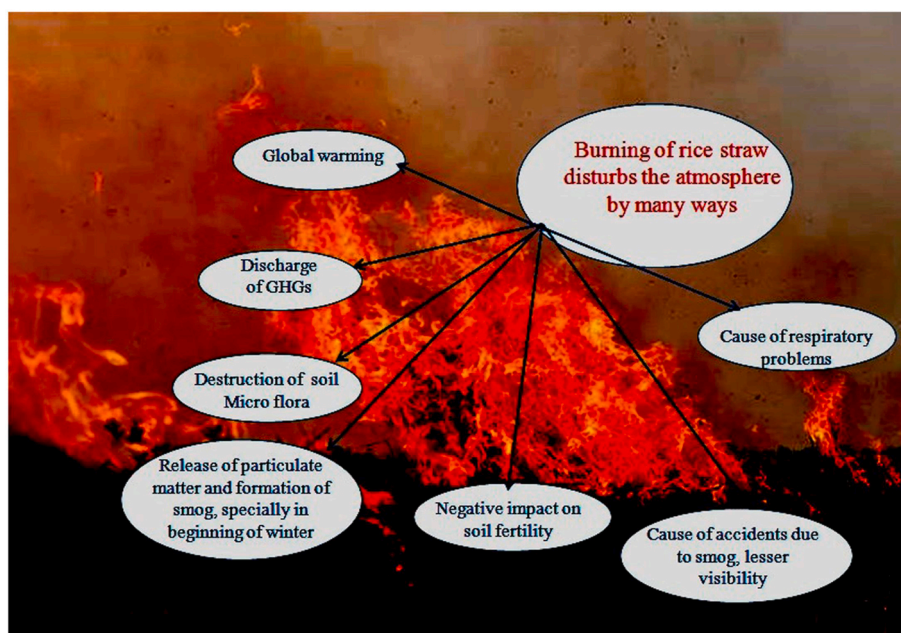


Fig. 1. Factors affecting the environment due to in situ rice-straw burning (reproduced from Singh and Arya [11], with permission from the publisher). GHGs: greenhouse gases.

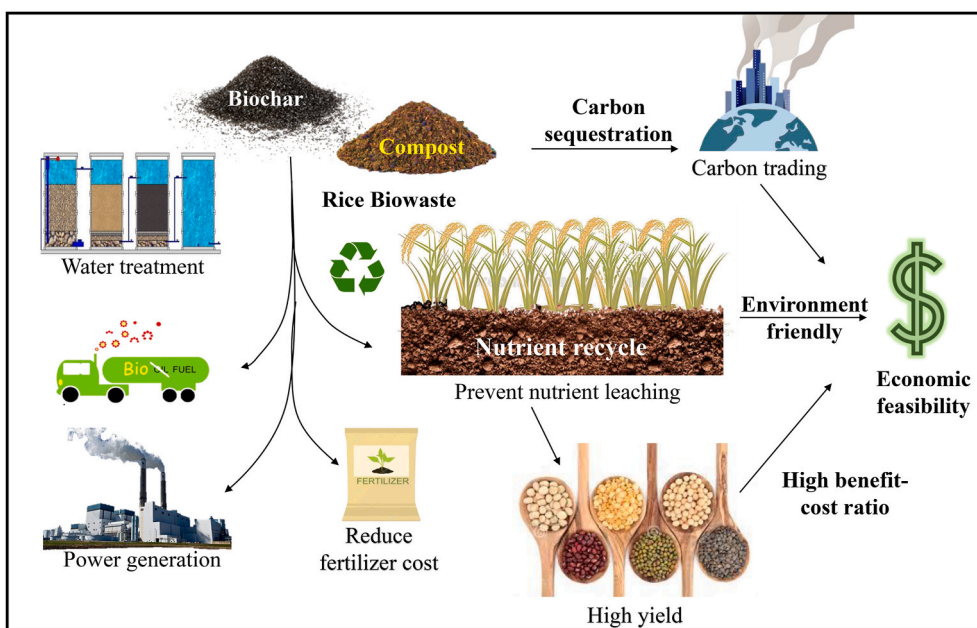


Fig. 2. Potential environmental applications of rice biowaste-based biochar and compost.

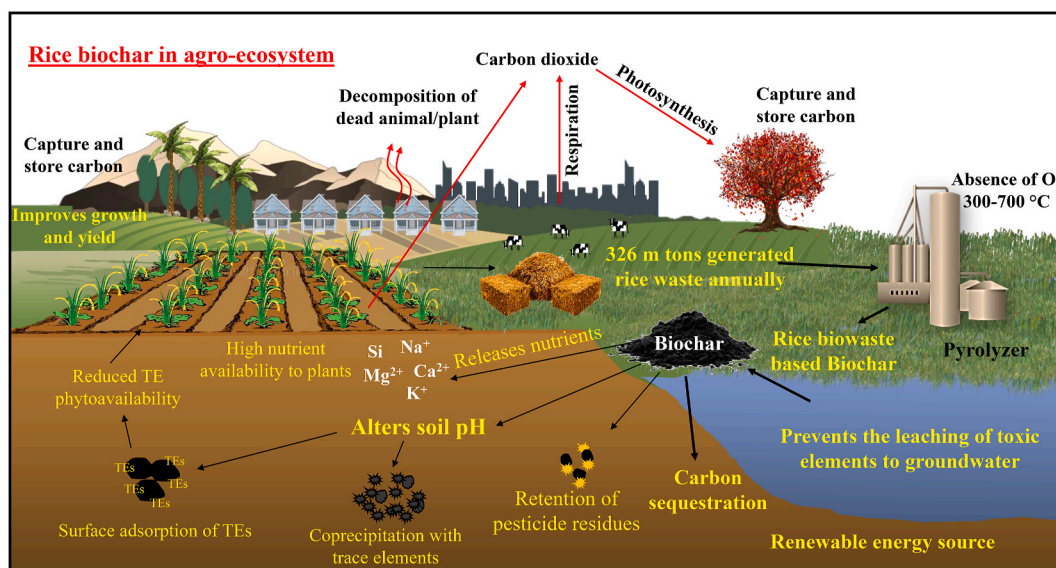


Fig. 3. Importance of RBC in agriculture and interactions with organic and inorganic pollutants in soil.

[26]. Multiple studies have demonstrated the effects of varying pyrolysis temperature and feedstock choices on BC yield (Table 2). For example, Biswas et al. [29] conducted a pyrolysis study on RH and RS as feedstock in a temperature range of 300–450 °C. Their results [29] showed a maximum yield of rice-husk biochar (RHBC) at 300 °C. As the pyrolysis temperature increased further, there was a corresponding reduction in RHBC yield, cation exchange capacity (CEC), and the content of hydrogen, carbon, and nitrogen [29,30]. The maximum RHBC yield observed at 300 °C was associated primarily with the removal of hemi-cellulosic and cellulosic compounds. Together with pyrolysis temperature, residence time also influences the production rate, BC properties, and total biomass yield. Likewise, the BC yield, oxygen-to-carbon (O/C) ratio, and acidic functional groups of BC reportedly decrease as pyrolysis temperature and residence time increase [31]. However, increases in several other variables (pH, surface area, porosity, carbon content, nutrient content, alkaline functional

groups, and water-holding capacity) were observed with increases in pyrolysis temperature and residence time. The mean BC pore size was larger when prepared at low temperatures and decreased gradually with increases in temperature (300–700 °C) [32,33]. From these observations, it can be inferred that BC with a high carbon content form at high pyrolysis temperatures. It is reasonable to conclude that BC with low hydrogen and oxygen content indicates the effect of carboxylation, dehydration, and de-carbonylation due to increased aromaticity [32, 34]. A residence time of 2 h at 300 °C achieved the maximum BC yield. Moreover, the yield and volatile-compound content of BC decreased with increasing temperature [35]. In contrast, Southavong et al. [36] showed that residence time (45, 60, and 120 min) had no significant effect on RBC yield. However, the maximum yield (48%) was obtained at a minimum temperature and time (300 °C and 45 min).

As biochar products are persistent and resistant to microbial degradation, their addition to soil may enhance carbon sequestration. It has

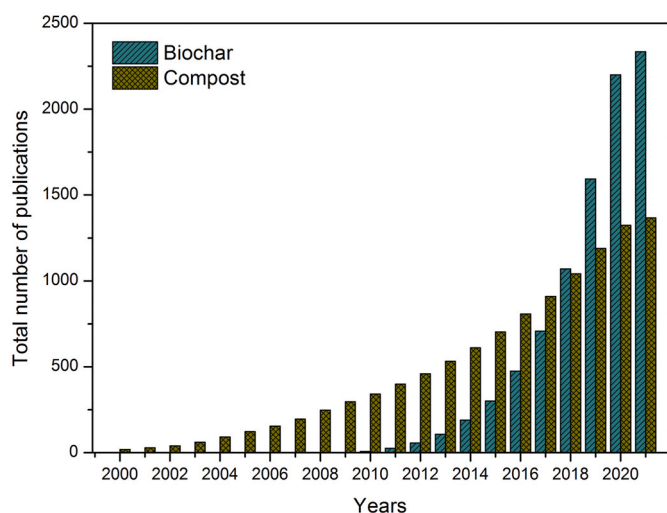


Fig. 4. Total number of published papers about rice feedstock-derived biochar and compost (based on the ISI Web of Science documents retrieved for the period from 2000 to 2021).

been suggested that the average degradation rate for biochar should be less than 0.3% per year [37], theoretically facilitating long-term storage of carbon (e.g., 100–1000 years) [38] (Fig. 3). Biochar is composed of amorphous and crystalline structures of joint aromatic compounds. The carbon skeleton that develops during pyrolysis of an organic feedstock is responsible for the porosity of the final product, giving the resulting BC its characteristic sponge-like structure [39]. The spaces are formed as pores of different sizes: macro- (>50 μm), meso- (2–50 μm), and micropores (<2 μm). The large surface area is due to the high percentage of micropores that can contribute to the storage of soil pore water [88]. The pore-size distribution on the surface of biochar greatly affects the sorption capacities of BC. The greater the pore volume, the greater the sorption rate of contaminants [58,79]. A number of functional groups are known to exist on BC surfaces, including carboxyl, carbonyl, and hydroxyl groups [64], all of which play important roles in adsorbing TEs (Fig. 3).

Table 1 summarizes global and country-wide rice production and rice waste generation. Considering the 50% yield of BC by pyrolysis of RS and RH, global BC production is 1,513,953,49 tons per year, enough to cover 151,395.0 km^2 of agricultural land (Table 1) at an application rate of 10 tons/ha or 1000 tons/ km^2 [89].

2.2. Rice biowaste-derived compost

Rice straw is a major agricultural waste product in rice-growing countries. The ability to recycle RS and husks is of great concern to those tasked with producing compost and improving soil. Composting organic waste is an interesting alternative to recycling as the obtained compost can be used as organic fertilizer. Compost tends to contain degraded substances and mobile/non-volatile nutrients; when applied to the soil, it can improve soil fertility and structure. In some cases, compost may contain TEs and other toxins that could lead to secondary contamination in soil. Compost derived from different feedstocks contains less organic carbon (11%–41%) compared with biochar derived from different feedstocks (24%–87% carbon), although the former generally has more nitrogen (0.64%–3.0% vs. 0.11%–2.2%), phosphorus (0.15%–3.29% vs. 0.01%–2.33%), and potassium (0.40%–3.55% vs. 0.13%–3.4%) compared with the latter [90]. Both rice biowaste-derived compost and biochar can therefore contribute to the enhancement of soil organic matter (SOM) content. However, the contribution of biochar to a stable soil-carbon pool is greater than that of compost.

Studies have been conducted on the formation and characterization

of RC [91,92]. For example, Wang et al. [91] conducted a study of rice straw-derived compost (RSC). The results showed an increase in pH and a decrease in the C/N ratio during the composting process. Earlier, Jusoh et al. [92] determined the effect of amended microbial communities on the process of RS composting to evaluate the compost quality. The application of microorganisms can enhance the composting process by increasing the micronutrient (e.g., iron) and macronutrient (e.g., nitrogen, phosphorus, and potassium [NPK]) contents of compost. The resulting product of this biological process is a pathogen-free, humus-like, and stable substrate that can be applied as an organic fertilizer. However, recent studies have focused on biochar production for CO_2 sequestration and remediation of contaminated soil and water [32, 93–95].

3. Characterization of rice biowaste-derived biochar and compost

3.1. Rice biowaste-derived biochar

Elemental compositions, such as the hydrogen-to-carbon (H/C) and O/C ratios, are useful indicators to describe the surface characteristics of BC. Varying experimental conditions affects the size, elemental composition, and functional groups of BC (Table 2). The chemical and physical properties of RHBC and rice straw-derived biochar (RSBC) pyrolyzed at different temperatures (400–800 $^{\circ}\text{C}$) were studied by Jindo et al. [96], who found that the highest yield was obtained at 400 $^{\circ}\text{C}$ for both feedstocks; RH produced the maximum yield. An elemental analysis showed higher carbon, hydrogen, oxygen, and nitrogen contents at this temperature, while concentrations decreased with increasing temperatures. The carbon, oxygen, and silicon contents of RSBC were 36.2%, 39.8%, and 17.8%, respectively [64]. Fourier transform infrared analysis showed a peak range of 1000 to 4000 cm^{-1} , confirming the presence of O–H, C=C, C=O, C–O, and C–H functional groups and various acidic groups. However, the elemental contents varied greatly by pyrolysis temperature. High temperatures resulted in high C/N ratios, indicating strong anti-degradation properties. Likewise, increased temperatures resulted in decreases in the O/C and H/C ratios, reflecting the decrease in hydrophilicity and aromaticity, respectively. Increasing the pyrolysis temperature may enhance the surface area per unit mass of the particles and decrease the H/C and O/C ratios [34]. Surface properties depend largely on pyrolysis temperature, feedstock, and residence time (Table 2). Surface characterization of biochar is therefore crucial to understanding its interaction with the matrix in which it is amended (soil/water) and the mechanisms for adsorption of contaminants (Table 2).

3.2. Rice biowaste-derived compost

Varying conditions can alter the chemical composition of compost. An increase in composting duration results in a decrease in feedstock carbon and an increase in nitrogen, which results in a decrease in the C/N ratio of the compostable material [97]. In an early work, Vuorinen and Saharinen [98] reported that approximately 11%–27% of the carbon is lost during the initial composting process and between 62% and 66% during the entire process in the form of CO_2 gas. The basic characteristics and elemental contents in RC are reported in Mahmoud et al. [99]. Thiyageshwari et al. [100] characterized RH compost (RHC) using scanning electron microscopy (SEM) to identify significant structural changes over time. The carbon content decreased from day 15 to day 90 of composting, while NPK increased significantly over time. The SEM images revealed a loose, rugged, and lumpy epidermis of the RH after composting. The duration of each step also changes the C/N and C/P ratios of the compost. Of utmost importance in composting is the stabilization of organic matter, resulting in fairly resistant carbon compounds.

Table 2
Biochar pyrolysis conditions, surface characterization and suitability for environmental applications.

Rice feedstock	Pyrolysis conditions	Characterization technique	Particle size/surface area	Functional groups/elements	Reference
Straw	500 °C, 2 h	BET, elemental analyzer	Surface area 16.98 m ² /g	C 56% O 29% H 2.3% N 1.1% H/C 0.48 O/C 0.52	[40]
Straw	500 °C, 2 h	SEM, IRTracer-100 infrared spectrum, BET	Surface area 19.96 m ² /g Pore volume 0.03 cm ³ /g Particle size 9.2 nm	C-H -CH ₂ OH C=O C-H C 49.61% H 4.74% N 1.03% O 10.91% H/C 1.15 O/C 0.44 (O + N)/C 0.18	[41]
Husk	430 °C	SEM, FTIR	–	-H -OH C=C C=O -OH CO-	[42]
Straw	300 °C, 1 h	BET, SEM	Surface area 48.3 m ² /g Pore volume 0.39 cm ³ /g Pore diameter 2.86 nm	C 68.72% H 5.02% N 2.08% O 24.18% O/C 0.35 H/C 0.07	[34]
Straw	400 °C, 1 h	BET, SEM	Surface area 78.4 m ² /g Pore volume 0.71 cm ³ /g Pore diameter 4.58 nm	C 75.47% H 4.63% N 1.98% O 17.92% O/C 0.23 H/C 0.06	[34]
Straw	500 °C, 1 h	BET, SEM	Surface area 101.3 m ² /g Pore volume 1.65 cm ³ /g Pore diameter 9.48 nm	C 81.48% H 2.34% N 1.24% O 14.94% O/C 0.18 H/C 0.02	[34]
Straw	300 °C, 1 h	BET, BJH, FTIR, XRD	Pore diameter 9.45 nm Pore volume 0.03 cm ³ /g Surface area 28.1 m ² /g Particle size 213.3 nm	C 48.13% H 1.53% N 1.00% S 0.383% O 48.96% O/C 1.02% H/C 0.032 C/N 48.06 (O + N)/C 1.04	[43]
Straw	600 °C	CHNS analyzer, SEM, EDS, FTIR	–	C 68% H 1.3% N 0.59% S 0.06% O 6.4% H/C 0.23% O/C 0.07 (O + N)/C 0.6	[44]
Husk	600 °C	CHNS analyzer, SEM, EDS, FTIR	–	C 69% H 0.9% N 0.52% S 0.01% O 5.3% H/C 0.16% O/C 0.06% (O + N)/C 0.58	[44]
Straw	550 °C, 2 h	Elemental analyzer, BET	Surface area 14.5 m ² /g	C 47.1% N 2.53% O 17.5% H 1.96%	[23]
Straw	500 °C, 2 h	SEM, FTIR	–	C-H C = C	[45]

(continued on next page)

Table 2 (continued)

Rice feedstock	Pyrolysis conditions	Characterization technique	Particle size/surface area	Functional groups/elements	Reference
Straw	500 °C, 2 h	SEM, FTIR, BET	Surface area 223.4 m ² /g Pore size 5–150 μm	O -H N 0.6% P 1.99% K 27.2% C 53.8% O 20.3% C 49% Si 25.9% K 6.6% Cl 2.6% Ca 2.98% Mg 1.2% Na 1.7%	[46]
Straw	350–600 °C, 1 h	SEM, CHNS Analyzer	Bulk density 0.64 mg/m ³	C/N 95.84 C 42.2% N 0.44% S 0.053%	[47]
Straw	450 °C, 4 h	FTIR, SEM, XRD	–	O–H C=O C–C CH ₂ SiO ₂	[48]
Straw	600 °C, 1 h	–	65.5 m ² /g	N 1.66% C 59.6% C/N 35.9% Na 0.26% N 2.65% C 7.9% H 1.6% H/C 0.203 C/N 3.0 K 0.04% Ca 0.32% Mg 0.52% P 0.12% Na 0.32%	[49]
Straw	550 °C, 2 h	CHN analyzer	–	N 2.65% C 7.9% H 1.6% H/C 0.203 C/N 3.0 K 0.04% Ca 0.32% Mg 0.52% P 0.12% Na 0.32%	[50]
Hulls	500 °C, 4 h	XPS, FTIR, XRD	Surface area 95.67 m ² /g Pore size 5.88 nm Pore volume 0.04 cm ³ /g	C 33%, O 13.5% H 2.22%	[51]
Straw	700 °C, 4 h	Elemental analyzer	–	C 81%, H 2.5%, O 15.6%	[52]
Straw	500 °C, 2 h	–	Surface area 38.1 m ² /g	C 51.9% H 18.4%	[53]
Straw	500 °C, 40 min	SEM, FTIR	Surface area 32.18 m ² /g Particle size 0.25–2 mm Pore diameter 2.98 nm	C 36.6% O 14.55 H 3.7%	[54]
Straw	600 °C, 1 h	Gas adsorption analyzer	Surface area 12.6 m ² /g Porosity 0.034 cc/g	C 46%	[55]
Straw	500 °C, 2 h	SEM	Surface area 41 m ² /g	C 52.6% O 35.2%	[56]
Straw	700 °C, 4 h	Elemental analyzer, SEM-EDS, FTIR, XRD	Surface area 41.4 m ² /g	C 43.3% H 1.5% O 14%	[57]
Straw	700 °C, 4 h	SEM-EDS	Surface area 161.18 m ² /g	C 53% H 0.6% O 7.6%	[58]
Straw	500 °C, 6 h	Surface area and porosity analyzer, elemental analyzer	Surface area 2.2 m ² /g	C–H C = C C = O Si–H	[59]
Straw	800 °C, 2 h	Elemental analyzer, TEM, NRM	–	C 58.1% H 1.35% O 12.2% C=C C–C C–H	[60]
Husk	700 °C, 3 h	Elemental analyzer, SEM, FTIR	Surface area 78.4 m ² /g Pore volume 0.009 cm ³ /g Pore size 3.7 nm	C 45.9% H 2.5% O 26.6% C=C C=O C–O–C C–O –OH	[61]

(continued on next page)

Table 2 (continued)

Rice feedstock	Pyrolysis conditions	Characterization technique	Particle size/surface area	Functional groups/elements	Reference
Straw	400–500 °C, 24 h	Brunauer–Emmett–Teller equation	Surface area 8.9 m ² /g	-CH ₂ -CH ₃ C 749 mg/g O 113 mg/g	[62]
Straw	700 °C, 2 h	SEM, FTIR, Elemental analyzer, BET	Surface area 369.2 m ² /g Pore volume 0.23 cm ³ /g Micropore volume 0.09 cm ³ /g Mesopore volume 0.14 cm ³ /g	C 31.8% H 0.98% O 7.23% C=C C=O C-O -OH	[63]
Straw	550 °C, 2 h	SEM, FTIR	Surface area 30 m ² /g	C=O C-O -OH -CH ₂ C-O-C	[64]
Husk	500 °C, 2 h	BET	Surface area 17.2 m ² /g	C 49%	[65]
Straw	350–550 °C	SEM, FTIR	Surface area 130.18 m ² /g Pore size 3.65 nm	-OH, C=O, C=C, C=C-H, C-O	[66]
Straw	500 °C, 1 h	Elemental analyzer, SEM	–	C 45% H 1.2%	[67]
Husk	700 °C	SEM-EDS	Surface area 226.8 m ² /g	C 46.3%	[68]
Straw	500 °C, 2 h	Elemental analyzer, Gas adsorption analyzer	Surface area 179.6 m ² /g	C 46.5%	[69]
Straw	700 °C	FTIR	–	C 60.8% H 1.2% O-H C-H C=O	[70]
Straw	550 °C, 1 h	Elemental analyzer, BET surface area analyzer	Surface area 81.8 m ² /g Pore volume 0.08 cm ³ /g Bulk density 0.13 g/cm ³	C 42.7%	[71]
Straw	800 °C, 0.5 h	Raman spectrum	Surface area 6.676 m ² /g	–	[72]
Straw	700 °C, 1.5 h	BET surface area analyzer, FTIR, XRD	Surface area 32.9 m ² /g Pore volume 0.05 cm ³ /g Pore size 59.2 nm	C 56.6% C=C C=O C-O-C C-O	[32]
Husk	400 °C, 0.5 h	–	–	C 36%	[73]
Husk	300 °C, 4 h	Elemental analyzer, FTIR, BET	Surface area 106.7 m ² /g Micropore area 91.8 m ² /g Pore volume 6.3 (10 ⁻² cm ³ g ⁻¹) Micropore volume 4.5 (10 ⁻² cm ³ g ⁻¹)	C 59.7% H 1.3% -OH C-O C=O	[74]
Husk	300 °C, 3 h	Elemental analyzer, FTIR, BET	Surface area 1.99 m ² /g Pore volume 0.007 mL/g	-CH ₂ C 48.3% H 25.1% O 2.3% C-O-C -OH -CO C-O=C	[75]
Straw	500 °C, 3 h	–	Surface area 14.5 m ² /g Pore volume 15.3 g/cm ³	C 29.3%	[76]
Straw	600 °C, 3 h	BET, SEM-EDX	Surface area 285.3 m ² /g Pore width 40 nm Pore volume 0.04 mL/g	–	[77]
Straw	500 °C, 0.5 h	BET, FTIR	Surface area 36.7 m ² /g	C 506 g/kg H 17.2 g/kg C=O C-O-C C-H	[78]
Husk	550 °C	SEM, FTIR	Surface area 20 m ² /g	C 48.7% H 1.24% O 2.47% C-C C-H	[79]
Husk	550 °C, 10 min	XRF, FTIR	–	C 50.9% H 2.0% O 10.1% O-H C-H C=O	[80]

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Table 2 (continued)

Rice feedstock	Pyrolysis conditions	Characterization technique	Particle size/surface area	Functional groups/elements	Reference
Husk	300 °C	Elemental analyzer, FTIR, BET	Surface area 1.39 m ² /g	C=C C 51.7% H 3.85% O 23.9% C-H, C=C C-C	[81]
Husk	900 °C, 4 h	Elemental analyzer, EGME, XRF, EDX	Bulk density 0.18 g/cm ³	C 40.9%	[82]
Husk	700 °C, 3 h	Elemental analyzer, FTIR, BET, SEM	Surface area 179 m ² /g Surface area 377 m ² /g Pore volume 0.05 cm ³ Pore diameter 5.29 nm	H 1.2% C 47.7% H 1.29% O 7.6% C=C C=O	[83]
Husk	550 °C, 2 h	Elemental analyzer, BET	Surface area 139.2 m ² /g	C 0.56 g/kg	[84]
Straw	500 °C, 8 h	–	–	C 620 g/kg	[85]
Husk	–	Elemental analyzer, SEM, EDX, FTIR	Bulk density 0.18 g/cm ³	C 34.8% O 32.3% -CH -OH	[86]
Husk	500 °C, 2 h	SEM, EDS	–	C 26.9% O 41.7%	[87]
Husk	550 °C, 2 h	BET	Surface area 139.2 m ² /g	C 0.56 g/kg	[84]
Straw	750 °C, 2 h	BET	Surface area 164 m ² /g	C 1 g/kg	[84]

BJH: Barrett-Joyner-Halenda, BET: Brunauer–Emmett–Teller, FTIR: Fourier transform infrared spectroscopy, EDX: Energy-dispersive X-ray spectroscopy, SEM: scanning electron microscope, XRD: X-ray diffraction analysis.

4. Agricultural applications of rice biowaste-derived biochar and compost

Reuse of RB can offer numerous benefits for agriculture, especially in the context of current global challenges. The increasing demands for food, fiber, and fuel to achieve food and energy security represent constant pressures on the soil. As SOM is a key factor affecting soil fertility and productivity, it also affects the soil-to-human continuum. As such, SOM must be maintained in equilibrium or improved through sustainable management to enhance soil health and productivity, which may consequently contribute to the achievement of SDG 2 (zero hunger). In this section, we review and discuss the agricultural applications of RB, particularly the effects of RB on SOM, carbon sequestration, soil properties and fertility, nutrients availability, and plant growth.

4.1. Impacts of rice biowaste-derived biochar and compost on soil organic matter

Soil organic matter comprises a variety of different pools, ranging from fresh plant and microbial residues to stable compounds (Fig. 5; 101), with different turnover rates making total soil organic carbon (SOC) less sensitive than labile SOC fractions in soil management, particularly in the short term [102,103]. The labile SOC fractions provide a multifunctional role of SOM required for major soil functions. Biochar applications generally increase SOC [104–109]; for example,

Yang et al. [110] reported that RSBC increases SOC by between 4% and 26% compared with an untreated control in a paddy with different soil layers. Although positive effects of BC on total SOC have been widely reported, these benefits do not appear to persist. For example, Oladele [106,107] tested different rates of RHBC and found an increase in soil surface SOC of up to 33% only in the first year, with a decline in the second year. In a three-year rice-based cultivation project, the application of RHBC increased SOC only after the first season, after which SOC declined to even lower levels than those of the control [111]. Examples of SOC responses to RB are summarized in Table 3.

Few studies have investigated the changes in SOC fractions in response to RB applications. However, Yang et al. [110] reported that labile SOC fractions, specifically water-extractable organic and microbial biomass carbon, increased by 52% and 41%, respectively, after RSBC application and controlled irrigation. Yang et al. [110] explained that the changes in labile SOC fractions induced fluctuations in SOC during the experiment. Similarly, Munda et al. [112] found that active SOC pools, specifically very labile and labile varieties, decreased with increasing RHBC application rate (0.5–10 tons ha⁻¹), while the passive fractions increased significantly only at higher RHBC application rates. Mavi et al. [113] reported that RBC increased the readily decomposable organic carbon, dissolved organic carbon content, and microbial biomass carbon in a pot experiment with a wheat-maize sequence, particularly at higher application rates.

Under field conditions, Haefele et al. [111] monitored the

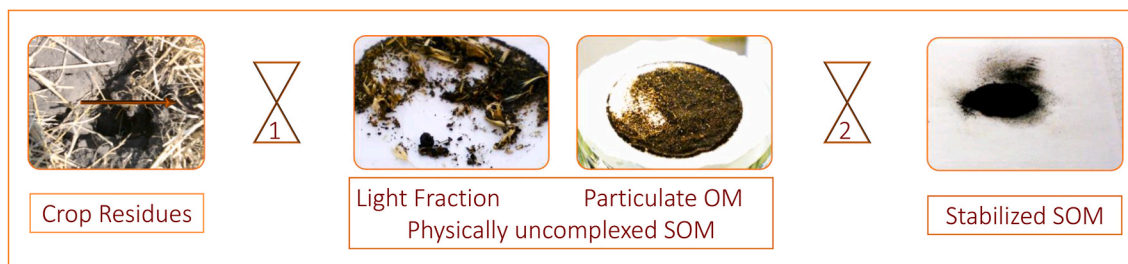


Fig. 5. Transformation of different pools of soil organic matter. Labile fractions (physically uncomplexed organic matter) as an intermediate stage between plant residues and stable soil organic matter. The quality and quantity depend on factors regulated by: (1) quantity and quality of inputs of residues and/or (2) environmental conditions and microbial activity (adapted from Gregorich et al. [101]; photos: H. Abdelrahman).

Table 3
Examples of soil organic carbon response to RBC and RC applications.

Rice biowaste	Production conditions	Soil description	Application rate	Study time	Soil organic C response	Reference
Straw biochar	Pyrolysis details are available in Yang et al. (2020) Pyrolysis of rice straw at 450 °C with a residence time of 1 h under oxygen-limited conditions Pyrolysis at 350 °C for 6 h using indigenous furnace at controlled temperature and restricted aeration in electrical muffle furnace at peak temperature of 500 °C and 30–45 min pyrolysis process Pyrolysis at 350–400 °C using an electric biochar reactor	Dark-yellow hydromorphic paddy soil, rice Rice paddy in Northeast China pH of 6.7 (1:2.5, water/soil, w/w), and average soil bulk density of 1.31 g cm ⁻³ , whereas the total soil N and total C concentrations were 1.2 and 11.0 g kg ⁻¹ soil Sandy clay loam texture Clay Loamy sand Medium-textured Typic Oxic Paleustalf Alfisol	20 and 40 ton ha ⁻¹ in a pot experiment 0–29.6 t ha ⁻¹ 0.5–10 ton ha ⁻¹ 1 and 3% in an incubation exp. 0, 3, 6, 12 ton ha ⁻¹	4 months 2-year 36 months 10 months 36 months	4–26% increase in SOC 58% increase on average in response to 29.6 t ha ⁻¹ biochar, as compared with the control 43–169% increase in total SOC 23 and 70% increase in clay soil 123% and 168% First year: 33% increase in SOC with 12 ton/ha in the 0–10 cm soil layer and 32% increase in the 10–20 cm layer Second and third years: decrease in SOC by 66% and 56%, respectively 28% increase Average increase of 2.22%	[110] [109] [112] [105] [106, 107] [114] [115]
Straw compost		Sandy loam Typic Ustipsamment	8 ton ha ⁻¹	12 month (crop cycle)		
Husk compost	Applied with or without basalt	Fine clayey, kaolinitic, isohyperthermic, Rhodic Hapludox, cultivated with cocoa seedlings	5, 10 and 20 ton ha ⁻¹	24 months		

mineralization of carbon into CH₄ in RHBC under anaerobic conditions for two years. They reported that RHBC application enhanced soil respiration only in the first rice crop by an equivalent of 0.14% of the applied RBC. This suggests that realistic RBC residence times may be in the range of thousands of years.

However, BC application does not always positively affect SOC fractions; it can also reduce the highly labile fractions of SOC, such as the dissolved organic carbon and microbial biomass carbon, and alter their chemical compositions [69,116] because the dissolved organic carbon, or some specific molecules of it, can become adsorbed on BC surfaces. Rice biowaste application in soil does not only increase SOC but also improves SOC quality. In an experimental attempt to promote cocoa growth, the quality of SOC was improved through the addition of RHC with increases in the O-alkyl, carboxyl carbon, and di-O-alkyl groups. Also, the addition of RHC may help improve the SOC quality through the generation of additional functional aromatic, alkyl, and methoxyl carbon groups [115].

4.2. Impact of rice biowaste-derived biochar and compost on carbon sequestration

Crop residues offer a reliable resource for energy [5,117,118], but depletion of SOC stocks poses a concern [119]. In recent decades, both RBC and RC have been perceived as promising and effective options for carbon sequestration in agricultural soils (Fig. 6; 117). Application of RS to paddy soil was found to improve soil quality and increase crop yields [120]. However, it also led to increases in CH₄ emissions, which contribute to global warming. Crop residues contain a significant proportion of labile organic carbon, which explains the contribution of RS to GHG emissions [121]. However, RSBC is generally characterized with a low H/C ratio, which makes it more suitable for carbon sequestration [32]. In a nine-year field experiment involving RSBC application, the labile fractions (10%–12%) of RSBC decomposed in the early (first to fourth) years, while a considerable proportion of the aromatic carbon decomposed at a later stage, supporting the potential of biochar for effective carbon sequestration, a characteristic that could only be assessed in experiments with a duration of more than five years [94].

The potential of RSBC to increase carbon sequestration depends on increasing the aromatic carbon content in native SOC and increasing its resistance to biodegradation via stabilization mechanisms [122,123]. The application of RSBC increases SOM aromatic fractions, i.e., particulate organic matter and humic acid fractions [123]. Furthermore, Wu et al. [122] suggested that RSBC increases carbon sequestration by altering exchangeable ion distribution in aggregate fractions and SOC chemical composition. The contribution of RSBC to carbon sequestration is more evident than the contribution of RS; a six-year double-rice-cropping trial revealed that RSBC effectively sequestered 19.4–27.2 t C ha⁻¹ against 3.96–7.44 t C ha⁻¹ after raw RS application [41]. In a four-year field study, Mehmood et al. [120] found that RS successfully improved crop yields, although SOC was not affected. However, a positive effect of RSBC on soil-carbon retention was observed in topsoil (0–30 cm depth). Straw incorporation in soil, when accompanied by potassium fertilization, improved the labile fractions of SOC and contributed to carbon sequestration in a six-year trial of continuous rice-wheat rotations [124] and in maize grown in a fragile ecological environment [125].

The response of soil and its native SOC to biochar application depends on the climate and the physiochemical and biological characteristics of the soil. RSBC, when compared with control treatments, clearly improved plant growth, enhanced carbon sequestration, and lowered GHG emissions in a study of six soils and five crop-rotation cycles [126]. Nevertheless, the effects of biochar on carbon sequestration depend on the pyrolysis temperature. Chen et al. [127] found that RSBC produced at 800 °C resulted in native SOC stabilization as the larger surface area of RSBC protected native SOC via adsorption. Biochar potential for carbon sequestration in soil is also climate-dependent; Chen et al. [127]

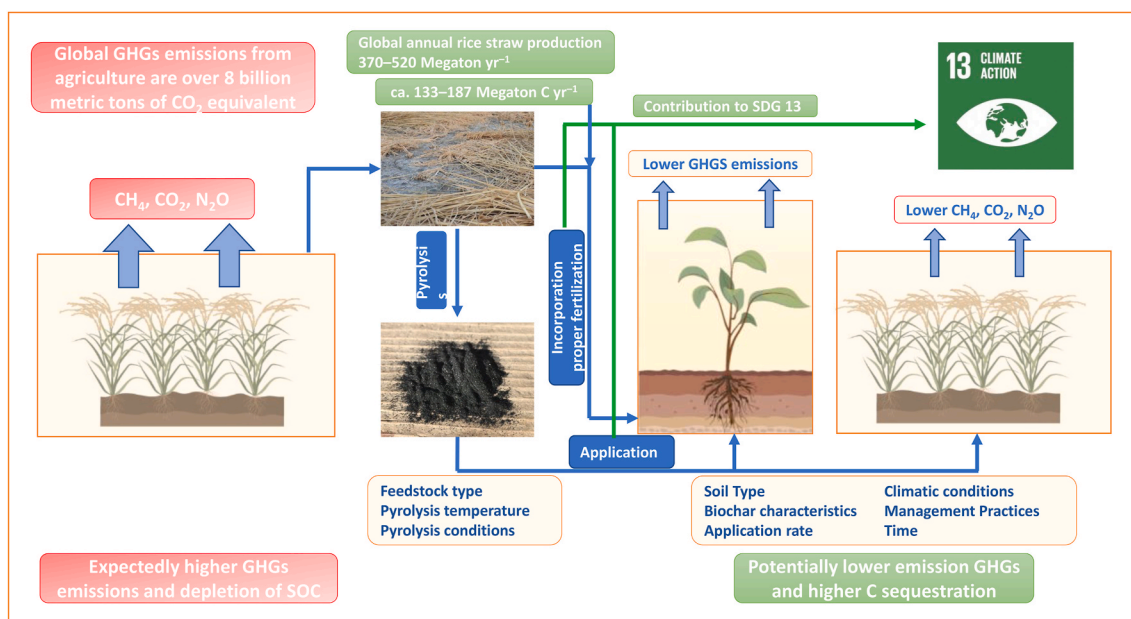


Fig. 6. Rice-straw management in relation to carbon sequestration in soil. Global annual rice-straw production is derived from Van Hung et al. [117] and its conversion to fixed carbon is based on an average of the fixed carbon range (33.7%–38.2%) in rice straw. The emission data are obtained from the FAO ESS Working Paper No. 2 (2014; available at <http://www.fao.org/3/i3671e/i3671e.pdf>).

suggested that RSBC is much more efficient for soil-carbon sequestration in cooler regions (i.e., 15 to 25 °C) whereas temperatures above 25 °C reduce SOC stabilization on BC active surfaces.

The addition of RBC to soil reduces GHG emissions, but its actual effects on carbon emissions and/or sequestration depend on the application rate [128]. Under controlled irrigation in a rice paddy, RSBC application increased soil respiration and total soil CO₂ emissions, particularly when added at high rates of 40 tons ha⁻¹; however, at 20 tons ha⁻¹ it significantly increased the net CO₂ input in soil, suggesting that the proper management of RSBC offers a great potential for carbon sequestration [129].

In their six-year trial, Zhang et al. [130] found that the RSBC-derived carbon sequestration rate decreased in the first two years and increased in subsequent years. The latter effect is possibly due to BC reducing the mineralization rate in bulk soil — and even in micro-aggregates — and to lowered enzyme activities and improved soil structure [130]. Biochar tends to bind the highly labile forms of SOC, such as water-extractable organic carbon or permanganate-oxidizable carbon [116,131].

Fewer reports involving RC are available in the literature compared with RBC studies, as the C/N ratio of RB is rather high and it is therefore usually composted with other lower-C/N biowaste materials. Nevertheless, one study [132] reports on the application of RS combined with RSC to mitigate GHG emissions from paddy soils through the reduction of CH₄ emissions and the accumulation of SOC. The combined application was unsuccessful, as GHG mitigation declined by 21% over time.

In line with the current global adoption of climate-smart agriculture practices, and as BC contains up to 70% organic carbon and most of this carbon is in a stable and recalcitrant form, BC can potentially provide more carbon compared with plant residues of the same mass. However, BC carbon's persistence in soil depends on feedstock type, pyrolysis temperature and conditions, soil type, and agricultural management practices. Long-term experiments and modeling solutions should therefore determine the relative persistence of BC in a soil-plant-microorganism system.

4.3. Impact of rice biowaste-derived biochar and compost on soil properties and fertility

The effects of RBC and RC on soil properties, fertility, and plant yield

are summarized in Table 4. The most important benefit of rice-waste biochar is related to its porous nature and high chemical activity due to its cation exchange capacity (CEC) (Fig. 7). This condition may increase the nutrient content and availability and decrease crop water requirements.

The mechanisms of RBC interactions with fertilizers and soil microorganisms with respect to nutrient immobilization, release, and plant uptake are summarized in Fig. 8. RBC adds significant retention capacity to soils with a naturally low CEC [137,152]. The increased water-holding capacity results in less-frequent irrigation requirements or smaller amounts of water [136]. Furthermore, the water-holding capacity of biochar increases with a decrease in pyrolysis temperature, an effect related to the enhanced O/C biochar molar ratio [145,153]. Soil amended with RHBC had a lower C/N ratio (i.e., denoting faster N mineralization) than soils amended with other biochars [145]. Among different biochars, RS and RHBC resulted in higher soil pH (initially slightly acidic), and higher total and Olsen soil phosphorus [143]. Moreover, NO₃-N decreased significantly compared with the unamended soils [106,107].

Retained substances in soils with RBC can include gaseous compounds in addition to nutrients and water. The retention mechanisms are mostly related to physical entrapment of gases into biochar pores. This is important with regard to soil-emitted gases, including NO_x (with x = 0.5 and 1), CH₄, and CO₂. For example, Wang et al. [147] found that RSBC decreased CO₂-equivalent emissions by approximately 13,000 kg ha⁻¹ compared with the unamended control in a four-year field experiment during which biochar was added at 48 ton ha⁻¹. However, some studies have reported the opposite; Sarfaraz et al. [137], for example, found increased CO₂-C emissions after adding RBC to an acidic soil in incubation experiment. Tarin et al. [135] found that added RBC influenced NO_x emissions, likely due to an increase in retained soil moisture, a factor contributing to the enhancement of such emissions. Selvarajh et al. [138] found that lower ammonia emissions could be achieved in an acidic soil amended with RSBC and RHBC at up to 20 ton ha⁻¹ compared with urea treatment in an incubation test.

An important property of biochar (including RB-derived varieties) is its typically alkaline pH [134]. Biochar is beneficial in neutral to slightly alkaline soils as it increases buffering capacity, enhancing a soil's ability to tolerate acid-producing activities, such as the application of certain

Table 4

Overview of the impact of rice waste-derived biochars and rice waste composts on soil properties, soil fertility, and plant yield.

Biomass feedstock	Pyrolysis temperature (°C)	Application rate/type of experiment	Soil type /plant	Impact	Reference
RSBC RHBC Straw vs. RSBC	300–400	5–20 t ha ⁻¹ (incubation); 5–10 t ha ⁻¹ (pot experiment) 6-year field experiment; rates up to 48 t ha ⁻¹	Acidic; in pot experiment:/rice Acidic, medium-textured soil/rice	Ammonia loss increased with BC, but lower than the urea treatment BC added more total organic C than straw at same amended rate. Rice yield was unaffected by amendments; also N use efficiency also remained unaffected	[133] [41]
RH-, wheat straw-, sugarcane baggass-BC Bamboo, hardwood, RS-BC	420–500	1.5%/pot and incubation experiment Up to 80 g kg ⁻¹ /pot experiment	Calcareous silt loam/silt Strongly acidic soil	BC increased Olsen-P, plant P and shoot biomass BC increased pH, caused a 4-fold increase in total C and N, decreased NOx emissions, but no differences at the end of the 6-month experiment.	[134] [135]
RSBC RHBC Swine manure-, poultry litter-, cattle manure-, RS-, soybean straw-, corn straw-BC RHBC	450	0.50 g BC kg ⁻¹ soil/pot experiment 1–2% of added C/incubation experiment	Sandy loam and silty loam Acidic, sandy loam	BC increased water-holding capacity, CEC, total N, and available P and K of soil Added BC increased CO ₂ -C emissions	[136] [137]
RH, poultry/wheat-straw BC	600	Up to 20 t ha ⁻¹ /Lab-scale closed air flow system Sorption experiment of NH ₄ -N, at MAC up to 500 mg L ⁻¹	Oryza sativa NA	BC decreased ammonia loss and increased N use efficiency compared to the treatment of added urea alone Sorption was dominated by NH ₄ -N entrapment (i.e., large pores led to higher retention); RH had the least ability to retain NH ₄ -N	[138] [139]
RHBC	NR	2-year field test; rate up to 100 t ha ⁻¹	Acidic, medium; sesame	BC increased plant yield, number of seeds per plant, plant K and N, and protein content. In soil, BC increased porosity, pH, exchangeable K, total N and CEC.	[140]
RH, corn-cob BC	300, 450, 650	Incubation for 90 d at 1%wt., then sorption; MAC = 86 mg P L ⁻¹ .	Oxisols (acidic), Ultisols (acidic), Entisols (neutral)	In BC, temperature increased C, N, and P content; in soil BC increased pH, OC and CEC; in sorption, BC in acidic soils decreased sorption maximum. Increased pyrolysis temperature increased sorption; BC decreased desorption.	[141]
RH, cotton sticks-, wheat straw-BC vs. farmyard manure, poultry manure and press mud.	400	Pot test at 2% wt.	Cd-spiked (at 50 mg kg ⁻¹) loamy alkaline; wheat and rice.	All amendments decreased DTPA-Cd and bioavailable Cd, and increased OC and CEC; pH increased more in BC, EC increased more in waste, OC increase was similar. RH-BC and press mud achieved better rice grain yield. Cd decreased more in RH-BC and press mud.	[142]
RHBC	NR	Field test; 0, 3, 6, 12 t ha ⁻¹ ; fertilizer at 0, 30, 60, 90 kg ha ⁻¹ .	Clayey Alfisols, sandy Ultisols; Upland rainfed rice	BC increased yield, 1000-grain-weight, decreased NO ₃ in clay, increased pH, N, OC, and available P and K; BC alone did not increase yield.	[106, 107]
RS, RH, soybean straw-, corn cob-, peanut shell-, wood-BC Hazelnut husk-RH co-composted and farmyard manure	NR	Pot test; applied rate NR Field experiment; rates NR	Sand, slightly acidic soil; <i>Brassica napus</i> . Soil NR; strawberry	BC increased pH (RSBC more), total P (RH-BC more) Olsen-P (RS-BC more), biomass (RSBC more), and P uptake (RSD-BC more) No differences among treatments of amendments in plant performance.	[143] [144]
RSBC	600	Sorption of P; MAC = 100 mg L ⁻¹ .	Ferralsols, acidic	BC increased pH, OC, CEC, DOC, Olsen-P; BC decreased P sorption sorption maximum, P buffering capacity, and point of zero charge from pH 7 to 5. RH and mill ash increased yield, sucrose content and improved soil properties; RH had better C/N.	[71] [145]
Mill ash vs. BC (hardwood yard waste, horse barn shavings, RH) Bamboo- and RS-BC vs. rice straw RH compost	350–400 600 (bamboo BC), 550 (RS-BC) NA	Lysimeter test; 1, 2% wt. Field test at 4.5C ha ⁻¹ . Pot test; 5 t ha ⁻¹ .	Sand; sugarcane Cold waterlogged paddy Two Alfisols; black gram (<i>Vigna mungo</i>)		
Straw-BC	500	Field test; 0, 24, 48 t ha ⁻¹ .	Hydragric Anthrosol; double-rice-cropping system.	Both BCs and RS reduced temperature fluctuations especially at 5-cm depth. RS did not increase rice grain yield; only RSBC did. RH increased grain yield by 16% and also protein content in grain. BC increased DOC (first only), OC, N, P, K, grain yield, decreased Eh. Net greenhouse-gas emission decreased by ca. 13,000 kg CO ₂ -eq ha ⁻¹ compared with the unamended control.	[100] [147]
RS, dicewood-BC (normal and acidified)	300	Leaching test; 0.5 g kg ⁻¹ .	Clay loam, highly saline-sodic, CaCO ₃ 9.3%	RSBC decreased EC from 15 to <1 mS cm ⁻¹ (DW-BC to ca. 8), SAR to 8 (from 16 mEqL ⁻¹) ^{0.5} (DW-BC to 14).	[66]
Green waste compost vs. RH-BC	450	Field test; 35 t compost and 10 t BC ha ⁻¹ .	Soil NR; peanut	Amendments increased seed yield, pod yield, root nodule number, dry nodule weight per plant, N, P, K, chlorophyll. In comparison, BC	[148]

(continued on next page)

Table 4 (continued)

Biomass feedstock	Pyrolysis temperature (°C)	Application rate/type of experiment	Soil type /plant	Impact	Reference
RS compost with growth-promoting microorganisms	NA	Field test; rates NR	Soil NR; rice	increased CEC, decreased EC, increased pH, OC, N, decreased soil C/N increased plant yield more than compost did. Rice yield improved with applied compost	[149]
RH-chicken manure co-compost	NA	Pot test (pots filled the compost)	Spinach	CEC = 176 cmol _c kg ⁻¹ , pH 7.9, EC = 1.2 mS cm ⁻¹ , C/N = 17; Fe increased in spinach leaves, but Cu–Mn–Zn decreased; N, P, K, Ca, Mg unchanged from normal peat.	[150]
RH and sewage sludge co-composted	NA	Pot test (10-d. growth); application rate in clayey soil: 0, 1, 2, 4, 6, 10, 20, 100%; in sandy soil: 0, 0.2, 0.8, 1.5, 3, 6, 100%.	Clayey and sandy soils; barley	Increasing rate of compost decreased pH, increased EC, soil N, OC, and decreased root/shoot ratio (i.e., promoted growth).	[151, 152]
RHBC	250–300	Field test; 10 t ha ⁻¹ .	Sandy, slightly alkaline, nutrient-poor soil; paddy rice.	BC increased water-holding capacity, total N, C, N, P, and plant growth (panicles, tiller number, grain yield, straw weight).	[153]
RSBC	500	Microcosm test; 2.5% wt.	Highly alkaline; rice	BC increased N ₂ O emissions and pH.	[154]

BC: biochar; Comp: compost; NR: not reported; RS: rice straw; RH: rice husk; NA: not applicable; MAC: maximum added concentration; SSA: specific surface area; OC: organic carbon; CEC: cation exchange capacity; DOC: dissolved organic C; EC: electrical conductivity.

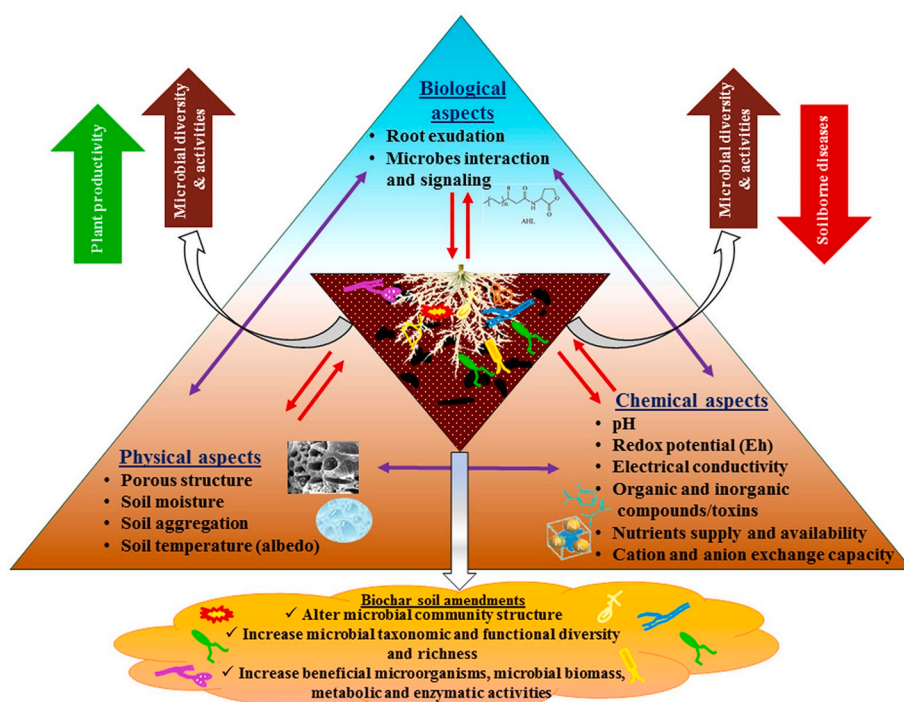


Fig. 7. A rhizosphere microbiome-centric view of the complex interactions between physical, chemical and biological components of the soil-biochar-plant-pathogen system. Biochar-induced changes in rhizosphere microbial structure, diversity, and activity may be associated with the direct or indirect effects of biochar on soil (i) physical aspects (porous structure, soil moisture content, aggregation, and temperature); (ii) chemical aspects including nutrient supply and availability, inorganic and organic compounds/toxins, pH, cation exchange capacity, electrical conductivity, and redox potential; and (iii) biological aspects (root morphology and exudates, interaction and signaling between microbes) of the rhizosphere.

inorganic fertilizers [71,106,107,141].

Some of the beneficial effects are similar to those of added non-charred organic materials. Azhar et al. [142] found that three tested biochars (RS, cotton stick, and wheat straw) had a beneficial effect on a soil comparable to the effect associated with non-charred farmyard manure, poultry manure, and press mud; they all increased organic carbon, soil CEC, and grain yields of rice and wheat in a pot experiment. Likewise, through a comparative field study of RC and RHBC, Zhang and Sun [148] found that biochar increased soil CEC, pH, and organic carbon to a greater extent than did compost, had a lower C/N ratio, and resulted in a more conservative increase in electrical conductivity. However, a distinct difference makes the charred materials superior to the uncharred: their stability over decomposition. This feature decreases the need for yearly application, as is often the case with manure. The fact that biochar resists decomposition also increases the carbon deposits in soil,

enhances CO₂-C sequestration, and decelerates carbon evolution to the atmosphere, shifting the carbon equilibrium to terrestrial ecosystems and altering the dynamics of GHG evolution.

4.4. Impact of rice biowaste-derived biochar and compost on plant growth and yield

Plant yields have repeatedly been found to increase in biochar-added soils compared with unamended soils. Singh et al. [153] found that rice yields doubled by increasing the RHBC dose from 2 to 4 ton ha⁻¹ [71, 147]. The reported data for upland rice are also similar: not only the yield increased but also important yield parameters (including the 1000-grain weight and number of panicles per m²) compared with an unamended control [106]. Concurrently, rice yields with added RBC increased due to reduced temperature fluctuations throughout the

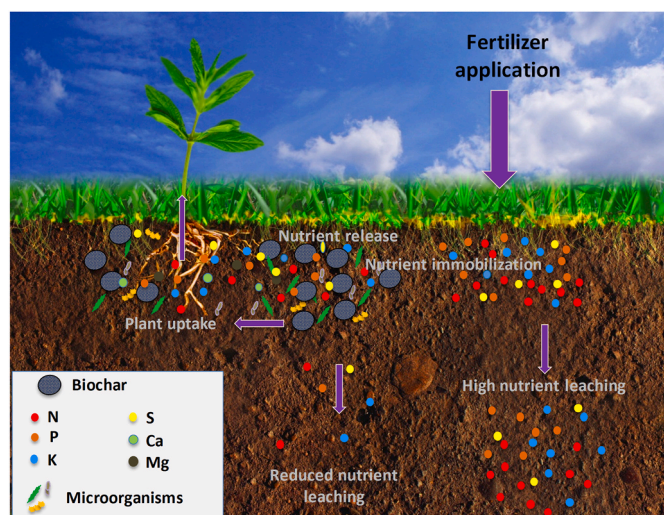


Fig. 8. Mechanisms of biochar interactions with fertilizers and soil microorganisms for nutrient immobilization, release, and plant uptake in process which is likely to improve soil fertility.

growing season [146]. However, Wang et al. [147] reported no significant effects of added RB-derived biochar on soil temperature. Results have been similar in other crops. In a canola crop, yields increased with a concurrent impressive two-fold increase in Olsen phosphorus in soil, likely due to biochar-borne phosphorus [143]. Yields also increased with RB-derived biochar addition [53]. Nutrient content in biochar appears to be related to charring conditions; Singh et al. [153] found that nutrients from RB-derived biochar increase with decreasing pyrolysis temperature. Apart from phosphorus, nitrogen-use efficiency also improves when wheat-straw biochar is applied to soils [133]. Similar findings were reported by Sumaraj et al. [139] for RB-derived biochar. However, their findings are far from conclusive: a six-year field study in paddy rice cultivation with biochar added at 48 ton ha^{-1} revealed that overall rice yields were unaffected by biochar, as was nitrogen-use efficiency [41].

The effect of RC (i.e., non-charred materials) on nutrient availability and plant growth is comparable to that of charred materials. For example, when soil was treated with water and chick manure co-compost in a spinach-pot experiment [150], the iron content of the spinach leaves increased, whereas copper, manganese, and zinc decreased (e.g., relative to a control treatment with normal peat). Elsewhere, in a pot experiment with black gram (*Vigna mungo*), it was found that RHC increased grain yield by 16% compared with un-amended controls [100]. Similar results were reported in experiments involving a barley pot [151], a strawberry field test [144], and a rice field [149].

One study that compared the effects of charred and non-charred organic materials in rice-paddy experiments tested bamboo and RSBC along with uncharred RS. Liu et al. [71] found that all tested materials had beneficial effects, but uncharred RS failed to increase rice yields. Zhang and Sun [148] compared green waste compost with carbonized RH prepared at 450°C in a peanut (*Arachis hypogaea*) field experiment; they found that the biochar increased seed yields, pod yields, and nodule numbers. Several studies have compared RBC with other composts. For example, Azhar et al. [142] tested farmyard manure, poultry manure, and press mud along with RH, cotton stick, and wheat-straw biochar in a pot experiment with wheat and rice; the researchers found that RBC and press mud produced the largest grain yields as well as root and shoot dry weight in both crops.

5. Environmental applications of rice biowaste-derived biochar and compost

The use of RB to remove organic and inorganic contaminants from aqueous media and soils is a promising and cost-effective technology. Among all raw RB materials, RS has attracted attention because of its high yields and carbon-rich content. In this section, we discuss the ability and efficacy of RBC and RC in remediation of water and soils contaminated with TEs and organic pollutants.

5.1. Remediation of toxic element-contaminated soils

An overview of various studies on the effect of rice-based BCs on the mobilization of TEs in soils is shown in Table 5. Due to the high retention capacity of RBC and its diverse active functional groups and high porosity, it can be used as a soil amendment to remediate soils contaminated with TEs. Numerous reports have reached this conclusion. Among many others, El-Naggar et al. [155,156] reported on anionic arsenic, molybdenum, and vanadium; El-Naggar et al. [157] on cationic cadmium, copper, nickel, and zinc; Lu et al. [78] on cadmium, copper, lead, and zinc; Rinklebe et al. [158] on silver, antimony, tin and thallium; and Xing et al. [159] on mercury.

The (im)mobilization efficiency of RBC depends strongly on its CEC; RBC with a CEC of $100 \text{ cmol}_c \text{ kg}^{-1}$ would be able to immobilize significant concentrations of TEs in soils. However, the real retention capacity of RBC depends on other parameters that are a function of the specific experimental conditions. A review by Barquilha and Braga [160] summarized these factors as follows: operating units (batch or continuous flow systems), solution pH, sorption temperature, co-existing ions and other substances, biochar particle size, initial added concentration and biochar dosage, contact time, and stirring techniques.

Biochar surface functionality also plays a vital role in TE (im)mobilization in soils. For example, biochar with large numbers of oxygen-containing functional groups was applied to immobilize vanadium with its solubility reduced by 46% [156]. As such, these authors were able to reduce the vanadium uptake by corn and sorghum by up to 86%. Application of rice-hull biochar which has few oxygen-containing functional groups increased vanadium solubility and biotoxicity. Its superior performance can be attributed to higher reactive surfaces, acidity, an abundance of various oxygen-containing functional groups, and the hydrophilicity of the former biochar.

Retention of TEs may depend on element species, BC characteristics, application rate, and plant species (if involved). Studies of this phenomenon are mainly of three kinds: sorption tests, incubation tests, and small-scale growth experiments in pots. Sorption tests unanimously agree that the retention efficiency of BC is greatly influenced by pyrolysis temperature: higher temperatures result in higher aromaticity (indicated by a lower H/C ratio and stronger BC structure stability), increased O/C (indicating higher hydrophilicity), and higher (O + N)/C (indicating higher polarity) [57,58,64,161–164]. Such alterations increase biochar pH to as high as 10.7 and increase specific surface areas up to $116 \text{ m}^2/\text{g}$; these in turn result in significantly higher total TE retention and faster retention kinetics (as was the case with lead in RSBC) [163]. Similar results have been reported in a cadmium-and-nickel sorption test using RSBC and RHBC [57,58,64]. Such tests also reveal the nature of retention of TEs; the suggested main retention mechanisms for TEs onto RBC (Bandara et al.) [165] are shown in Fig. 9.

We explored the impact of RBC on the mobilization of cadmium [166] and mercury [159]. According to Xing et al. [159], applications of RHBC at 24 t ha^{-1} and 72 t ha^{-1} immobilized total mercury (THg) and methylmercury (MeHg) in a paddy and reduced their accumulation in rice plants. Mercury is thought to be immobilized through binding with thiols (e.g., cysteine), which are either RHBC- or soil-borne (Fig. 10). According to Zong et al. [166], the retention mechanisms are (a) precipitation and co-precipitation with anionic phases, such as CO_3^{2-} and

Table 5

Overview of impact of rice waste-derived biochars and composts on the (im)mobilization of potentially toxic elements in contaminated soils.

Biomass feedstock	Pyrolysis temperature (°C)	Application rate/type of experiment	Soil type/plant	Element	Impact	Reference
RS-unmodified, and P-modified-RS-BC	Unmodified at: 300–550; modified: 300–500	60-day incubation experiment at added rate of 5%	Uncontaminated soil with Cd = 0.23 mg kg ⁻¹	Cd	Cd content in BC relative to that in initial feedstock increased with charring temperature; BC produced at higher charring temperatures has lower DTPA-extractable Cd	[166]
RSBC	500	Pot experiment; rates at 0, 5 and 10 g kg ⁻¹ soil	Cr-contaminated, slightly acidic soil/rice	Cr	Added BC accelerated Cr(VI) reduction to Cr(III) in both aerated and hydromorphic conditions; added BC increased rice yield and decreased rice Cr	[167]
RH, and iron oxide-modified-BC	400	Pot experiment; rates of up to 1.6%	As-contaminated, acidic soil/ <i>Oryza sativa</i>	As	Soil CEC increased from 15 to 21 cmol. kg ⁻¹ at the highest rate of added BC; soil As was not affected by BC; As in all plant parts decreased	[152]
RS-unmodified-, RS-acid-modified-, RS-alkali-m.-BC	500	Sorption at 1:800 ratio with AMC 10–120 mg L ⁻¹ ; also 60-day incubation with up to 5%	For the incubation, acidic soil	Zn	Kinetics equilibrium within 400 min; incubation: pH increased from 4.5 (control) to ca. 7 at 5%; also soil organic C; available (DTPA) Zn decreased by a factor of ca. 2	[162]
RHBC	600	Pot experiment at 1% BC with irrigation variations (continuous/intermittent)	As-contaminated soil/Rice	As	Added BC decreased As in both irrigation schemes	[168]
RH, corn-straw BC	400–600	Sorption with AMC of 5–1000 mg L ⁻¹	NA	Cd	Kinetics: monolayer sorption, chemisorption-dominated. Precipitation with minerals was predominant in equilibrium	[161]
RSBC	400, 700	Sorption onto BC; MAC = 200 mg L ⁻¹ ; 1-to-1000 ratio.	NA	Cd, Ni	Temperature increased sorption; maximum Cd sorption = 65.4, max. Ni = 54.6 mg g ⁻¹ . Mechanisms: precipitation.	[58]
RS, palm BC modified with β-cyclodextrin	500	Sorption onto BC; MAC = 5000 mg L ⁻¹ ; 1:50 ratio.	NA	Pb	Max sorption = 131 (RS-), 118 mg g ⁻¹ (palm BC); RS achieved faster kinetics than palm. Sorption by ion exchange and retention onto –OH and –COOH functional groups	[169]
RSBC	300, 500, 700	Sorption onto BC; MAC = 20 mmol L ⁻¹ ; 1:200 ratio.	NA	Pb	Sorption by precipitation; temperature increases sorption, stable Pb fraction and decreases exchangeable fraction.	[163]
RHBC	500	42-day incubation experiment; 5% added BC to soil	Contaminated sandy soil	As, Co, Mo	Added BC decreased the mobile fraction of Co and Mo, but increased that of As. Added BC increased As and Co in the dissolved phase in the oxidizing conditions	[155]
RS, sewage sludge BC	300, 500, 700	Sorption onto BC; MAC = 200 mg L ⁻¹ ; 1:1000 ratio.	NA	Cd	Temperature made sorption faster; sorption mechanism = precipitation (RS-) and cation-π interactions (sludge-BC).	[57]
RS, wood, bamboo, Chinese walnut-shell BC	500	Pot experiment, 5%wt	Heavy metal (Cd, Pb, Zn)-contaminated slightly alkaline soil; Moso bamboo	Cd, Cu, Pb, Zn	BC increased shoot dry weight (not with bamboo BC); more effective was RSBC. With BC metals decreased in bamboo shoots (not with RSBC) and soil solubility.	[53]
Corn straw-, wheat straw-, RS, licorice root pulp-BC	500	Sorption; added in soil at 3%, incubated for 90 d. MAC = 600 mg L ⁻¹ , ratio 1:10.	Sandy, calcareous	Pb, Cu, Ni	Sorption: Pb > Cu > Ni. RH rated worse than all tested BCs.	[170]
RS, swine manure co-pyrolyzed BC	400	Incubation; 3%wt.	Pb–Zn-contaminated soil	Cd, Cu, Pb, Zn	BC increased pH, EC, DOC, decreased metals extracted with CaCl ₂ in the order of Pb > Cu > Zn > Cd. BC decreased metal exchangeable fraction and increased carbonate-bound fraction	[171]
RHBC	500	42-day incubation experiment; 5% added BC to soil	V-contaminated soil	Cd, Cu, Ni, Zn	Added BC increased the dissolved fraction of all metals, especially in the oxic conditions; however, BC did not affect the colloidal fraction of the metals	[157]
RSBC	NR	Sorption onto BC	NA	Co	At low pH: sorption by inner-sphere complexes; at high pH: precipitation. BC increased amount of sorbed Co, but not sorption kinetics.	[172]
RSBC modified with H ₂ O ₂ and HNO ₃	800	Sorption onto BC (MAC = 550 mg L ⁻¹), 1:200 ratio	NA	Cd	Modified: 93.2 mg Cd g ⁻¹ maximum sorption; non-modified: 69.3 (at MAC). Modification increased acidic functional groups and SSA	[64]
RS, RH-, maize stover BC	500	Pot test; 1.5, 3%wt	Contaminated Ultisol acidic soil; Chinese cabbage	Cd	BC increased pH, OC, soil nutrients, decreased cabbage shoot Cd by 27–30%, bioconcentration factor and transfer factor.	[65]
RSBC and lime	500	Pot test; 2.5, 5% lime; 0.6, 1% BC	Pb-contaminated soil; <i>Oryza sativa</i> L.	Pb	BC increased pH, lowered CaCl ₂ -extracted Pb, Pb in shoots, increased rice grain weight and soil OC.	[69]
RS, coconut BC	NR	2-year field test; up to 22.5 t ha ⁻¹ .	Acidic soil; paddy rice	As, Cd	Coconut- better than RSBC. BC increased pH, OC and decreased Cd in rice. As did not decrease. Grain yield unaltered over the 2 years.	[63]

(continued on next page)

Table 5 (continued)

Biomass feedstock	Pyrolysis temperature (°C)	Application rate/type of experiment	Soil type/plant	Element	Impact	Reference
RS, maize-stalk BC (fine, moderate, coarse sizes)	500	Pot, 4%wt.	Yellow loamy ferrasol; <i>Brassica chinensis</i>	Cd, Zn, Pb, As	BC decreased metals in NH_4NO_3 extraction and plant due to increased pH; RSBC immobilized metals more than maize-BC; BC increased shoot biomass; fine BC was better than coarse.	[173]
RSBC	450	Incubation for 2 weeks at 0, 1.5, 3, 5% wt; then pot test.	Loam, slightly alkaline; <i>Triticum aestivum</i>	Cd, Ni, Zn, Mn	BC increased pH, Si content in plant, plant height, spike length, shoot and root dry mass, grain yield and photosynthetic pigments; decreased Cd and Ni, but increased Zn and Mn.	[174]
RS, bamboo BC	500 (RS), 750 (bamboo)	Incubation at 0, 1, 5% wt.	Heavy metal (Cd, Cu, Pb, Zn)-contaminated sandy soil	Cd, Cu, Pb, Zn	BC decreased CaCl_2 and DTPA extractions; RS was more effective in reducing metals.	[78]
RSBC	500	Growth in greenhouse soil at 0, 10, 20 t ha ⁻¹ .	Soil-1: lightly polluted; soil-2: highly polluted; lettuce	Cd	BC increased pH, OC, exchangeable Cd, and increased oxide-, organic-, and residual fractions. In soil-1 leaf Cd decreased, but in soil-2 leaf Cd increased.	[175]
RS, castor-BC	NR	Incubation for 60 d at 1, 2, 3% wt.	Soil spiked with 400 mg kg ⁻¹ Pb and Cu.	Pb, Cu	BC decreased acid soluble fraction of Pb, and castor fared better than RS; Pb was immobilized more than Cu.	[176]
RS, bamboo-, wheat straw-BC	750	Pot; at 2% (bamboo-BC); 1% (other BCs)	Spiked with Cd-Pb, acidic soil; maize, ryegrass	Cd, Pb	BC increased pH; no effect on maize biomass; Cd in soil decreased in RSBC (not in other BC); Pb decreased in all BC treatments.	[177]
RS, water hyacinth-BC	450	Leaching after 1-m. incubation; at 2, 5% wt.	Multi-metal contaminated soil	Cd, Pb, As	With BC, synthetic precipitation leaching procedure: Cd, Pb and As increased; KH_2PO_4 -As increased; CaCl_2 -Cd and -Pb decreased due to increased pH; Pb leaching in water hyacinth-BC increased.	[178]
Chicken slurry-RS comp.	NA	Pot test	<i>Spinacia oleracea</i> grown on peat and compost.	Cu, Fe, Mn, Zn	Metals increased in comp. compared to peat	[179]
RH, cotton straw-BC	300, 400, 500, 600, 700	Sorption onto BCs; MAC = 100 mg L ⁻¹ .	NA	Cd	Sorption by ion exchange and cation- π interactions. Temperature increased sorption and kinetics pace	[164]
RS comp. and phosphogypsum	NA	Pot test; 0.1, 0.2% wt.	Contaminated vertic torrifluvents; canola	Cd, Zn, Ni, Pb	With BC extractable P increased; Zn-Zn-Pb decreased in both amendments.	[181]

BC: biochar; Comp: compost; NR: not reported; RS: rice straw; RH: rice husk; NA: not applicable; MAC: maximum added concentration; SSA: specific surface area; OC: organic carbon; AMC: added metal concentration.

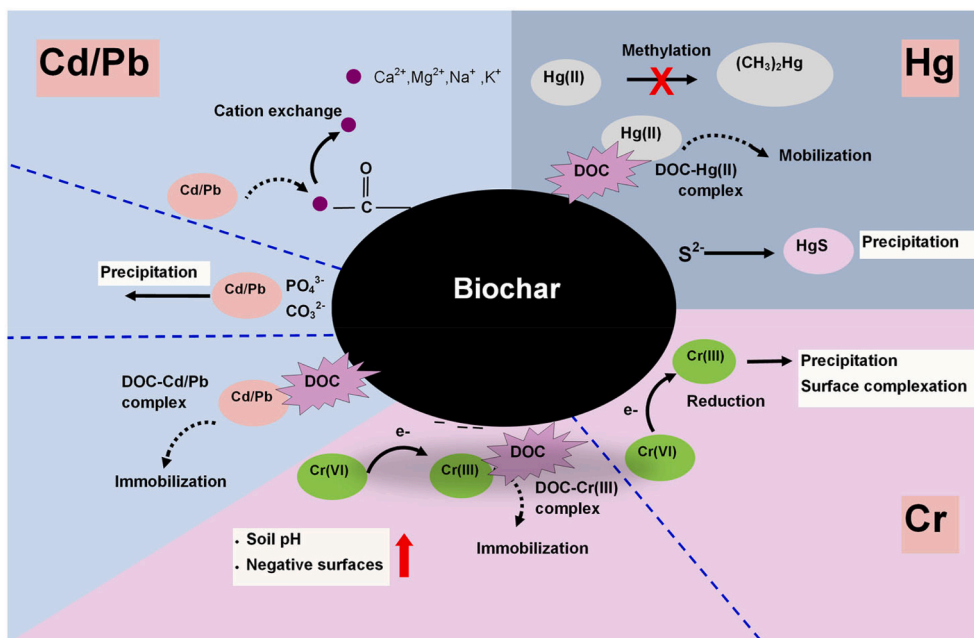


Fig. 9. Mechanistic illustration of Cd, Pb, Hg and Cr sorption by biochars in soil. DOC: dissolved organic carbon (Reproduced from Bandara et al. [165], with permission from the publisher).

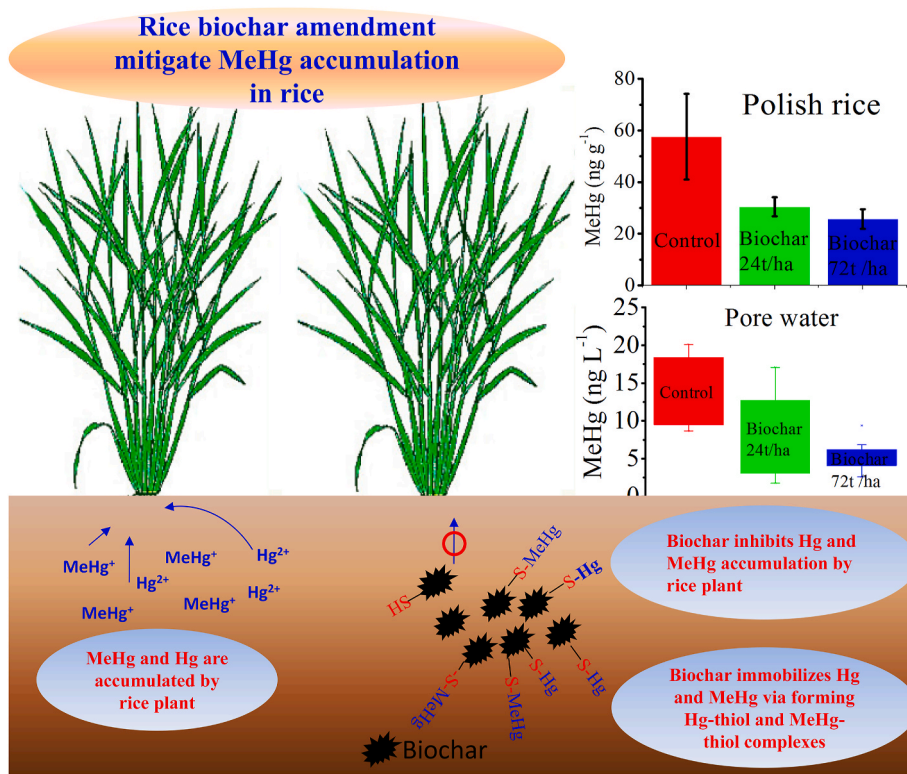


Fig. 10. Effects of the application of RHBC at 24 t ha⁻¹ and 72 t ha⁻¹ on total Hg and methylHg immobilization in a paddy field and their accumulation by rice plants.

PO₄³⁻; (b) physical retention via entrapment in BC pores; (c) surface electrostatic interaction; and (d) complexation with organic reactive groups (carboxylic and phenolic groups); the latter two involve ion-exchange reactions and may be defined as chemisorption. A conceptual graph describing TE retention by BC is shown in Fig. 11.

Several studies have shown that precipitation is the predominant retention mechanism when high-temperature biochar is used; indicating that TE immobilization on RBC depends on the pyrolysis temperature [58,163,182]. For cadmium, precipitation was the predominant

mechanism, even at charring temperatures of no more than 600 °C in an experiment with RBC and corn-straw biochar [161]. Retention mechanisms are influenced by solution pH, with sorption at higher pH values dominated primarily by precipitation and those at lower pH by chemisorption of ion species such as Cd(II) [165,172] and Co(II) [172]. Some studies have found that the zeta potential and C/H ratio, instead of specific surface area, are the decisive factors in NH₄⁺ retention on biochar [183].

The ability of RBC to retain TEs can be improved with modification

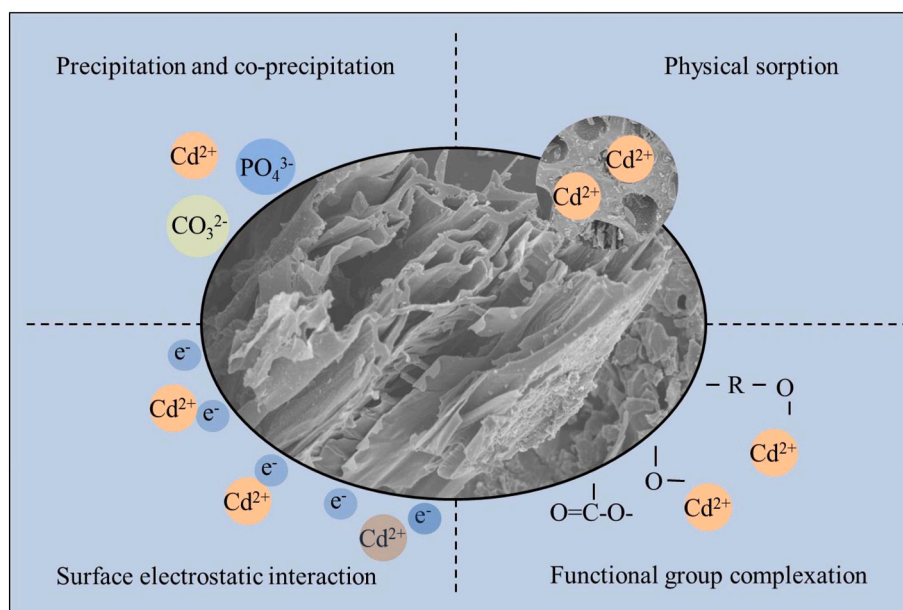


Fig. 11. Conceptual illustration of Cd immobilization mechanism onto biochar (Reproduced from Zong et al. [166], with a permission from the publisher).

techniques that enhance the O/C molar mass of biochar, while most –O functional groups are deprotonated carboxyl (-COO⁻) and phenolic (-O⁻) groups. The increase in active oxygen groups in modified biochar may facilitate metal chemisorption to form inner-sphere irreversible organo-metal complexes. This enhances the immobilization efficiency of biochar for TEs in soils. The maximum sorption of lead by β -cyclodextrin-modified RBC is reportedly higher (131 kg g⁻¹) than in palm BC (118 kg g⁻¹) [169]. In addition, Zhang et al. [64] observed an increase in maximum cadmium-sorption capacity from 69.3 mg/g to 93.2 mg g⁻¹ as RSBC was modified with H₂O₂ and HNO₃.

Rice straw-derived BC improves the retention of anions such as Cr (VI); in Qian et al. [184] RSBC (pyrolyzed at 300 °C and 500 °C) was amended to zero-valent iron, an effective solid that retains Cr(VI) through a variety of mechanisms, most important of which is the reduction of Cr(VI) to Cr(III) with the concurrent oxidation of Fe(0) to Fe (II) or Fe(III). They found that RSBC pyrolyzed at 500 °C increased Cr (VI) retention. A widely unnoticed remediation mechanism induced by added RSBC in Cr(VI)-contaminated soils is its accelerated reduction to Cr(III) in either water-logged or well-aerated conditions [167]. Likewise, arsenic content in *Oryza sativa* plant parts decreased when an acidic and arsenic-contaminated soil was amended with up to 1.6% RHBC [152]. This was corroborated by Kumarathilaka et al. [168] in RHBC-added soil in a pot experiment with cultivated rice.

Incubation and growth experiments are primarily concerned with TE extractability, mobility, and availability to plants. In a 150-day incubation test, Meng et al. [171] found that addition of RSBC decreased significantly the CaCl₂-extracted lead, copper, zinc, and cadmium compared with unamended controls.

A number of field trials conducted to examine the effects of biochar on plant growth and metal content, were reviewed by O'Connor et al. [185]. They found that the yield of test plants increases, while at the same time arsenic, cadmium, copper, nickel, lead, and zinc content in plants decreases, in soils amended with RBC. Bashir et al. [65] added ESBC and RHBC (3%w/w) to cadmium-contaminated soil with *Brassica chinensis* L. in a pot experiment. They found that adding biochar caused an impressive halving of CaCl₂-extractable cadmium, and a decrease of cabbage cadmium content by approximately 25%, as well as a decrease in the bioconcentration factor (i.e., cadmium in plant over cadmium in soil) and translocation factor (i.e., cadmium in aerial plant part over cadmium in roots), with RSBC more effective than RHBC [65]. Reducing TE mobilization and phytoavailability using RBC was reported for lead in *Oryza sativa* [69], for copper, lead, zinc, and copper in moso bamboo (*Phyllostachy pubescens*) [53], and also by Zhao et al. [186] concerning lead and zinc content in leaching water.

RBC is often compared with other BCs by according to their ability to retain TEs. Some studies have found non-significant differences in the effects; in a pot experiment with Chinese cabbage, Bashir et al. [65] found that RSBC, RHBC, and maize-stover BC had similar beneficial effects in reducing cadmium in plant shoots. Similar findings comparing RHBC and cotton-straw BC were reported by Jia et al. [164]. When Gao et al. [57] compared RSBC with sewage-sludge BC in a cadmium-sorption test, no significant differences were evident between the two tested BCs. However, other researchers have reported differences between RBC and other BCs: Wang et al. [53] studied the effects of RSBC, wood-chip BC, bamboo BC, and Chinese walnut-shell BC on cadmium, copper, lead, and zinc and on moso bamboo growth in a pot experiment. They found that RSBC was more effective than the other BCs at increasing bamboo yield and reducing metal content in shoots and metal solubility in soil. Likewise, Zheng et al. [173] reported that RSBC decreased cadmium, zinc, and lead content in *Brassica chinensis* to a greater extent than did maize-stalk BC. However, when Boostani et al. [170] compared corn-straw BC, wheat-straw BC, and RSBC in sorption tests with lead, copper, and nickel, they found that rice BC was the least effective at reducing metal sorption. The results for arsenic and cadmium sorption as reported by Chen et al. [63], who compared RSBC and coconut BC in a two-year field experiment with a rice crop, were similar.

In addition, RC effectively eliminated TE content in soils and plants. Omar et al. [179] found that copper, iron, manganese, and zinc content increased significantly in *Spinacea oleracea* compared with a control peat treatment in a pot experiment with RSC and chicken slurry, and plant height and dry weight were higher in the compost treatment. The contents of zinc, cadmium, and lead in canola significantly decreased in a pot amended with RSC and phosphogypsum [181].

5.2. Removal of inorganic contaminants from water and wastewater

The use of RBC to remove inorganic contaminants from aqueous media is a promising and cost-effective technology [93]. Among all the raw RB materials, RS has attracted much attention because of its high yields and rich carbon content.

5.2.1. Removal of phosphorus- and nitrogen-bearing compounds

An overview of studies of the effect of raw and modified RBC on the removal efficiency and mechanisms of nitrogen- and phosphorus-bearing compounds in water is shown in Table 6. For the removal of nitrogen, chemisorption is the main mechanism of adsorption of NH₄⁺ and NO₃⁻ by biochar [187–190]. For NH₄⁺, ion exchange and chemisorption are the primary mechanisms for removal by biochar from aqueous solutions [189]. As for NO₃⁻ adsorption, it is favored primarily by the presence of potassium, iron, and calcium ions carried on modified biochar surfaces through electrostatic attraction between oppositely charged ions [190]. The adsorption process for phosphorus by RSBC is different from that for nitrogen, as reflected in the adsorption of phosphate through intra-granular diffusion, followed by chemical adsorption [191]. Precipitation is the main mechanism of phosphorus removal by calcium- and magnesium-doped RBC, which mainly removes the element by co-precipitation and struvite crystallization [192].

Rice-straw biochar prepared at different pyrolysis temperatures exhibits different adsorption efficiencies for nitrogen and phosphorus. The adsorption of phosphorus by RSBC pyrolyzed at 300 °C is faster than that by BC pyrolyzed at 650 °C, which can be attributed to its higher CEC and lower iron and aluminum content. Increasing pyrolysis temperature increases the adsorption capacity of phosphorus [191].

Overall, RSBC pyrolyzed at a high temperature (e.g., 700 °C) demonstrated a superior ability to remove phosphorus than those RSBC produced at a low temperature, while low temperatures (e.g., 400–500 °C) are more effective at NH₄⁺-N removal [44,188,193]. This can be attributed to the surface-area enhancement induced by pyrolysis and could counterbalance the loss of functional groups, which is the principal mechanism for the NH₃-N removal and monolayer adsorption of NH₃-N favored by BC at pyrolysis temperatures of 400 °C [187].

In view of the limitations of the adsorption process by original BC, some measures have been taken to improve the adsorption effect of RSBC on nitrogen and phosphorus in wastewater, such as soaking and magnetic modification. Although the surface area of BC after magnetic modification is slightly reduced, its phosphorus adsorption capacity (25–28 mg P/g) is almost twice that of the original BC (12–15 mg P/g) [194]. In recent studies, acid- and alkali-modified RSBCs exhibited effective removal rates for NH₄⁺-N and phosphorus by increasing the types of O-bearing reactive groups on BC to provide more adsorption sites [195]. The removal of NH₄⁺-N and phosphorus on RSBC modified by chemical reagents, specifically HNO₃, HCl, H₃PO₄, and NaOH, at pH values between 6 and 7.5, were 69.5%–83.4% and 64.3%–89.7%, respectively [195–197].

The most commonly used modification methods also include loading of some metal particles or materials with special affinity for nitrogen and phosphorus on RSBC. Chandra et al. [190] found that potassium-modified RSBC achieved stronger adsorption abilities for nitrate, phosphate, and ammonium ions compared with raw biochar. In addition, MgCl₂-modified RSBC achieved a significantly higher removal rate of NH₄⁺ compared with raw RSBC [189]. Different modification methods can improve the physico-chemical properties and adsorption

Table 6
Adsorption of N and P by RBC.

Raw material (Biochar(s)/ Feedstock(s))	Dose	Modification properties	Adsorption kinetics	Adsorption isotherms	Findings	Reference
Cocoa pod husk (CP), corn cob (CC), RH, palm kernel shell (PK)	0.5 g/30 mL	unmodified	–	–	The adsorption of P was initially controlled by intra-particle diffusion, followed by chemical adsorption.	[191]
Rice straw (RSBC), <i>Phragmites communis</i> (PCB), sawdust (SDBC), and eggshell (ESBC)	0.2 g/20 mL	unmodified	–	–	The adsorption capacity of P can be increased by adjusting the pyrolysis temperature.	[193]
RH	0.05 g/mL	unmodified	–	–	Ca and Mg content of biochar is the key to P removal, and biochar with higher Ca and Mg content is more conducive to P capture.	[206]
RH	2 g/L	unmodified	–	–	The adsorption process is an exothermic reaction, and the removal rate of phosphate is as high as 89%.	[196]
RS	5 g/L	unmodified	–	–	The optimal pyrolysis temperature for $\text{NH}_3\text{-N}$ removal is near 400 °C.	[187]
Pine sawdust (PS)	20 g/L	unmodified	–	–	The PS-300 showed the highest $\text{NH}_4^+\text{-N}$ adsorption capacity (5.38 mg/g)	[207]
Fruit juice residue; RH	3 g/L	Soaking with 0.1 M NaOH + 0.1 M H_2SO_4 solution, washing and drying. Dry in 105 °C oven	Pseudo-first-order kinetic model	Freundlich model	Active rice husk: 89.65%; Rice husk: 64.27%	[197]
RH	0.25 mg/mL	$\text{Ca}(\text{OH})_2$ modified	Pseudo-second-order kinetic model	Langmuir isotherm	197 mg P/g	[208]
RS	0.01 g/40 mL	Modification of Eggshell as Calcium Source	Pseudo-second-order adsorption model	Langmuir isotherm	231 mg P/g	[209]
RH	0.3 g/L	$\text{Mg}(\text{OH})_2$ /bentonite modified	Pseudo-second-order adsorption model and the Weber–Morris model	–	125.36 mg P/g; 58.20 mg N/g	[192]
RH	10 g/L	Fe(II) and Fe(III) magnetic modification	–	Freundlich model	25–28 mg P/g	[194]
RS	0.2 g/200 mL	$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ modified and alkali reduction technique	Pseudo-second-order kinetic model	Langmuir–Freundlich isotherm	67.65 mg N/g	[190]
RS + clay	1 g	Mixing clay, biochar, Na_2SiO_3 , and NaHCO_3 by using different proportions	Pseudo-second-order kinetic model	Freundlich model	N removal efficiency was 88.6%	[210]
RS	0.05 g/50 mL	Soaking with 1.0 M of NaOH solution at a solid-to-liquid ratio of 1.0 g–2.5 mL for 2 h	Pseudo-second-order kinetic model	Freundlich model	N removal efficiency 69.5%	[195]

performance of RBC to varying degrees. Different modification methods can be used at the same time when preparing modified RBC to improve its effectiveness.

5.2.2. Removal of toxic elements

In recent decades, TEs in water and soil have been recognized as health risks to humans, animals, and plants [93,95,198–201]. RSBC has been used successfully due to its adsorptive behavior for TEs in aqueous solutions. Ding et al. [202] showed that RS has the potential to remove cadmium from large-scale effluents contaminated with TEs. Gao et al. [57] analyzed the relative contribution of Cd^{2+} adsorption mechanisms for RSBC and its high adsorption capacity compared with sewage-sludge biochar. The main cadmium-adsorption mechanism was Cd^{2+} ion exchange with K^+ , Na^+ , Mg^{2+} , and Ca^{2+} coupled with chelation with functional groups such as C=C, C=O, O–H, and carboxylic acids [57, 202,203]. Adsorption by RSBC is weak because of surface homogeneity, which can be overcome with modification protocols. Table 7 describes the adsorption effect of RS on TEs after the application of chemical modification techniques. However, these modifications can themselves lead to contamination. Fortunately, milder and more environmentally friendly “biomodification” techniques are available using bacteria, actinomycetes, and fungi [204]. For example, the bacterial strain *Comamonas testosteroni* FJ17 has been used with RBC for copper removal, increasing the retention capacity of RBS for copper by up to 27.4% [205].

5.3. Removal of organic pollutants from water and wastewater

Pollution by oxygen-demanding waste in water bodies refers primarily to the discharge of wastewater containing organic pollutants from urban sewage, agricultural activities, and the manufacturing of food and paper [218]. These contaminants consume dissolved oxygen during bio-oxidative decomposition. Non-biodegradable contaminants, which accumulate in aquatic organisms, can cause long-term environmental and health effects [219]. This section discusses the latest progress on organic contaminant removal using RBC in different water matrices and their mechanisms. Table 8 summarizes the performance of RBC for removing organic pollutants.

5.3.1. Removal of dyes

The annual production of synthetic dyes is increasing worldwide because of growing demand for colorful consumer products. The discharge of inappropriately treated wastewater during the production of dyes causes serious water pollution and health problems. Existing physical, chemical, and biological treatments are far from satisfactory in terms of degradation rate, cost-effectiveness, and the generation of secondary pollutants [220]. Recently, biochar produced from RBs using pyrolysis has been applied to dye removal. In general, the adsorption of dyes onto RB-derived biochar involves electrostatic and $\pi\text{-}\pi$ interactions, as well as the formation of hydrogen bonds.

Rice-husk biochar can reportedly eliminate malachite green dye from a water matrix, with its adsorption capacity depending on

Table 7
Sorption of TEs by RBC.

Raw material (Biochar(s)/ Feedstock(s))	Dose	Modification properties	Adsorption kinetics	Adsorption isotherms	Findings	Reference
Poplar wood Corn straw Cotton straw Wheat straw RS	0.66 g/L	Unmodified	–	–	Corn straw showed the highest sorption capacity to Cd followed by cotton straw, wheat straw, rice straw, poplar wood shaving.	[211]
RS	1 g/L	Unmodified	–	–	Magnetization of the biochars did not change the applicability of their respective adsorption models, but reduced their adsorption capabilities.	[212]
RS	5 g/L	Ethylenediamine tetra-acetic anhydride (EDTAD) and loading of Fe ₃ O ₄	Second-order kinetic models	Langmuir	Pb (II): 163.93 mg/g Zn (II): 84.74 mg/g Cd (II): 28.1 mg/g	[213]
RS	20 mg/L	Chemically activated	Rice straw biochar have greater CEC and surface area.	Langmuir	Cd (II): 41.9 mg/g	[214]
RS	–	Modified with FeCl ₃	Pseudo-second kinetic model	Langmuir isotherm	Cd (II): 26.9 mg/g	[215]
RS	50 mg/L	MnO _x -loaded	Pseudo-second kinetic model	Langmuir isotherm	Cu (II): 49.41 mg/g Zn (II): 53.42 mg/g	[216]
RS	100 mg/L	A high-yield cellulose bacterial strain <i>Comamonas testosteroni</i> FJ17	Both physical and chemical adsorption processes	Freundlich	Cu (II): 28.4 mg/g	[205]
RS	1–50 mg/L	Nanocellulose fibers	Electrostatic interaction with the divalent cationic metal species.	Freundlich and Langmuir model	Pb (II): 94.2%, Cd (II): 90.7%, Ni (II): 85.5%	[217]

carboxylic groups. Eltaweil et al. [221] indicated that mesoporous magnetic corn straw-derived biochar can achieve a maximum adsorption performance of 515 mg/g for malachite green. The surface area, pore diameter, pore size, and total pore volume of magnetic corn straw-derived biochar are 80.1 m²/g, 6.59 nm, 3.7 nm, and 0.127 cm³/g, respectively. Similarly, the adsorption of hazardous azo-rhodanine dye onto RS-derived fly ash under highly acidic conditions (pH 2) is due to strong electrostatic interactions between dye anions and the adsorption sites of biochar [222]. A monolayer adsorption capacity of 124 mg/g was achieved using RHBC, which was considered a value-added adsorbent for the elimination of acid red from polluted water. At present, a novel and cost-effective sludge-RH biochar (sludge: RH = 1:1) has been produced to remove dyes. Direct red 4BS adsorption on sludge-RH-derived biochar exhibited the highest capacity, followed by acid orange II, react blue 19 and methylene blue [223]. The adsorption rate of dye by sludge-RH-derived biochar is higher than that of acid and reactive red dyes [223]. The adsorption efficiency for reactive red 195 A dye (RR-195A) and malachite green dye from different water samples, when measured by modified switchgrass biochar, was more than 90% [225]. Biochars including RBC appear to have great potential for eliminating dyes from aqueous solution [225].

The adsorption/oxidation mechanism has been proposed as an effective removal option for malachite green dye [221]. The adsorption process usually followed three steps. In the first stage, the dye molecules diffuse rapidly from the bulk solution to the biochar composite surface until saturation. In the second stage, dye molecules enter the cavities of the biochar composite. In the third stage, the dye molecules slowly diffuse into the cavities of the biochar composite until equilibrium is reached [222]. Oxidation is also involved in dye removal. The oxidation of biochar particles during the removal process may lead to the decolorization of dye [224,225].

5.3.2. Endocrine-disrupting chemicals and personal-care product removal

Endocrine-disrupting chemicals (EDCs) and personal-care products (PPCPs) in aquatic environments are among the most commonly detected pollutants [226]. It has been reported that these compounds cannot be completely biodegraded and removed at conventional sewage treatment plants [227,228]. As EDCs and PPCPs are widely used, their

concentrations tend to increase in drinking water and water/sewage treatment plants [229], and options for their removal are of great interest.

Adsorption is one of the main mechanisms for the removal of EDCs and PPCPs from water [229,230]. Biochars such as RBC can be used for the adsorptive removal of EDCs and PPCPs [229,230]. For example, Wang et al. [226] recommended high-temperature pyrolyzed RSBC to remove 17 β -Estradiol (a common EDC) from polluted water. In a study by Ahmed et al. [230], the efficiency of functionalized wood biochar was examined for sorptive removal of six phenolic EDCs. Their findings suggest that the sorption of EDCs matched pseudo-second-order and external-mass-transfer diffusion processes by forming H-bonds along with π - π electron-donor-acceptor (EDA) interactions at different pH values.

In a study by Zheng et al. [231], RHBC's adsorption capacities for tetracycline from water were successfully modified using methanol. It was determined that π - π interactions between the biochar and contaminants increased the adsorption capacity for tetracycline by changing oxygen-containing groups in modified biochar. Similarly, adsorption of ibuprofen by rice straw-derived biochar was also studied by Salem and Yakoot [232], who found that RB-derived biochar is suitable for removing pharmaceutical compounds from contaminated water.

The adsorption properties of sulfamethoxazole (SMX) on RSBC have also been studied. Rice-straw biochar, which achieved its maximum adsorption capacity at a pH of approximately 3, gradually lost its adsorption capacity as pH increased due to the development of stronger electrostatic repulsion [235]. As for levofloxacin, the ability of RHBC to remove this substance from aqueous solutions was spontaneous and endothermic [81]. In another case, RSBC was found to shorten the time required to achieve adsorption equilibrium. A higher adsorption capacity of biochar was also found for SMX, although this capacity decreased for chloramphenicol [240]. Chemically treated rice-husk particles are applied as fillers in the manufacture of composite materials, which are of great significance to the mechanical properties of the materials. The performance of rice husk-reinforced composites was optimal after benzoyl chloride treatment. Composites with 30% (by weight) rice-husk filling were found to be the most suitable among the artificial composites studied by Naik et al. [241]. For example, magnetic

Table 8
Removal of organic contaminants in aqueous solutions by BC and the mechanisms involved.

Group	Contaminants	Adsorbent	Water matrix	Pyrolysis conditions	Operating conditions	Initial conc. of adsorbate	Removal efficiency (%)	Removal mechanisms	References
Color and dyes	Direct red 4BS; Acid orange II; React blue 19; Methylene blue	Sludge-RH biochar	Wastewater	500 °C/2 h	pH 10, 25 °C	200 mg/L	–	Electrostatic interaction, π - π EDA interactions; hydrogen bond	[224]
	Azorhodanie dye	RS fly ash	Wastewater	120 °C/48 h	pH 2, 25 °C	20–100 mg/L	35.0%–85.0%	Electrostatic interaction	[222]
	Methylene blue	RSBC	Aqueous solution	–	pH 5, 37 °C	400 mg/L	59.6%	Morphology and responsible functional groups interaction	[233]
	Malachite green	RHBC	Aqueous solution	260–340 °C/0.3 h	25 °C	20 mg/L	67.6%	Electrostatic attraction; π - π EDA interactions; hydrogen bond; Van der Waals attraction	[234]
EDCs and PPCPs	Bisphenol A	RHBC and rice-bran BC	Wastewater	300 °C/7 h	pH 7.6, 25 °C	2500 mg/L	94.3%	Electrostatic interactions; hydrophobic sorption	[235]
	Sulphamethoxazole	RSBC	Aqueous solution	600 °C/6 h	–	20 mg/L	–	Interaction of surface hydroxyls	[236]
	Triclosan	RSBC	wastewater	400 °C/4 h	pH 7, 25 °C	50–500 mg/L	–	Electrostatic interactions; hydrophobic sorption	[237]
	Phenol	RSBC	wastewater	400 °C/4 h	pH 7, 25 °C	50–500 mg/L	–	Electrostatic interactions; hydrophobic sorption	[237]
	Levofloxacin	RHBC	Aqueous solution	300 °C; 600 °C	pH 8, 30 °C; 45 °C; 60 °C	15–200 mg/L	–	π - π EDA interactions	[81]
Pest-icides	Carbofuran	RHBC	Drinking water	700 °C/3 h	pH 5, 30 °C	50 mg/L	47.7%	Electrostatic interaction; Hydrogen bonding; π - π EDA interactions	[83]
	Chlorpyrifos	RHBC	Wastewater	700 °C/1.5 h	pH 7.90, 25 °C	2.8 mg/L	93.7%	Electrostatic interaction; Hydrogen bonding; π - π EDA interactions	[238]
	Glyphosate	RHBC	Drinking water	700 °C/2 h	pH 4, 25 °C	20 mg/L	82.0%	Hydrogen bonding; pore diffusion; π - π EDA interactions;	[239]
	Glyphosate	RHBC	Drinking water	700 °C/2 h	pH 10, 25 °C	20 mg/L	56.0%	Electrostatic interactions; Hydrogen bonding; pore diffusion; π - π EDA interactions; Electrostatic interactions	[239]

RSBC and RHBC exhibited high bisphenol A (BPA) removal due to high iron crystallinity and large surface areas. The BPA degradation efficiency of rice-bran magnetic biochar can reach 94.3%. A synergistic effect of biochar and H_2O_2 allows for successful enhancement of BPA removal efficiency [235].

5.3.3. Removal of pesticides

The widespread use of pesticides in agricultural production increases the generation of pesticide-contaminated wastewater and its subsequent transfer to surface waters and groundwater. Uncontrolled production (factory areas), storage, and consumption of pesticides, particularly in low-income countries, can lead to pollution in aquatic systems [242]. RSBC has been considered a potential adsorbent for the removal of the frequently detected pesticides in aquatic environments [83]. The effect of RBC application on pesticide fate in soil is reported in Khalid et al. [28] and shown in Fig. 12. RSBC exhibited relatively high removal efficiency on atrazine (37.5%–70.7%) and imidacloprid (39.9%–77.8%) [243,244]. However, the adsorption capacities of RBC produced from the same source may vary. It has been shown that the atrazine removal efficiency of RHBC was 50.7%–58.8% and that of RSBC 42.2%–48.5%, while that of imidacloprid was 42.2%–57.7% for RHBC and 33.6%–39.4% for RSBC [243,244]. Biochar aromaticity, polarity, pore size, and pH are therefore crucial parameters controlling the pesticide adsorption performance of RBC [245]. The removal mechanism is considered to be the reversible combination or chelation of the solute and the organic carbon content of the adsorbent. Interception of the adsorbed molecules in the mesoporous or microporous structure of biochar may also play a role in removal mechanisms, such as reversible binding, sequestration of solute to organic carbon, and physical entrapment of molecules in meso- or micro-porous structures within the mineral structures of the adsorbent aggregates [5]. Possible retention mechanisms and fate of pesticides by RBC are reported in Khalid et al. [28] and presented in Fig. 13. In conclusion, the safe recycling of RB in agricultural and environmental applications may help restore, promote, and maintain sustainable use of terrestrial ecosystems for the ultimate achievements of SDGs.

6. Applications of rice biowaste-derived biochar in the construction industry

Waste minimization and carbon footprint reduction are at the forefront of cutting-edge research on the form of both biofuel production and manufacturing energy efficient materials from waste. Although the

processing of these materials is costly in terms of economy and energy, the net benefits far outweigh the costs.

Use of biochar as a construction material has recently been explored and promising advances have been made [246,247]. The use of RBC in the construction industry may contribute to the achievement of SDG 9 (industry, innovation and infrastructure). Table 9 summarizes the available data on the use of RHBC in construction and building materials. Although RBC is a diverse material, carbon is still the main constituent. The properties of RBC do not allow incorporation into cement at high percentages, but even a marginal addition has been found to be beneficial without compromising the strength of the cement. Biochar from wood and food waste in mortar have also produced optimal results when added at 1% as a partial replacement of cement. Biochar obtained from rice waste, by comparison, has sometimes been found to reduce mixture strength, an adverse effect that depends on the source of the RBC in the mortar-based composites. Akhtar and Sarmah [246] reported RBC inclusion in concrete from three different waste sources (poultry litter, pulp and paper mill sludge, and RH) at rates from 0.1 to 1% of total concrete volume. Flexural strength of the concrete improved substantially in most specimens; however, splitting tensile strength showed optimal results for RH char at 0.1 and 0.5%. The compressive strength exhibited a decreasing pattern at all replacement percentages compared with control specimens.

Given the potential applications in diverse sectors, attempts have been made to utilize RBC [246–248,251]. For example, Akhtar and Sarmah [240] demonstrated that RHBC at 0.1% of total volume was the most suitable replacement binder with respect to mechanical strength of the concrete. The cost of concrete production in the UK has been estimated to range from US\$146.5/m³ to US\$148.4/m³ when RHBC is added at rates of 0.1%–1% of total volume. Elsewhere, Muthukrishnan et al. [249] investigated the possibility of mixing mortar with RHBC to improve its physical properties. The authors showed that a combination of RHBC and RH to replace 10% and 40% by weight of RH ash exhibited improved mechanical and durability properties of the produced mortar.

One of the important aspects of RHBC is its pozzolanic properties and high content of silica fumes, which makes it an effective filler material for use as a partial replacement for sand or cement [247,250]. For example, a study by Zeidabadi et al. [250] showed that when RHBC was pretreated with a solution containing potassium, calcium, and magnesium at various proportions, an overall increase in the strength of the concrete was observed. This result can be attributed to pozzolanic reactivity with amorphous silica.

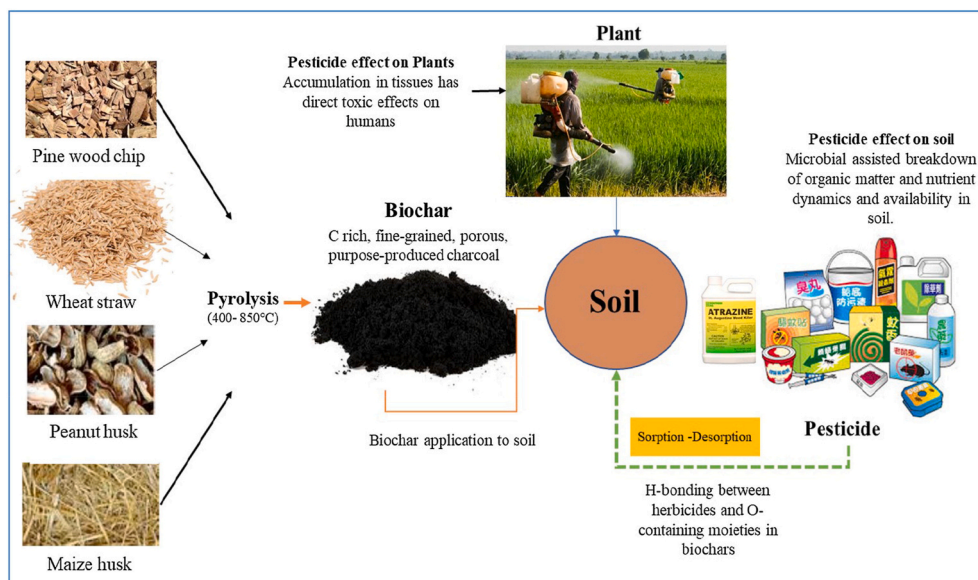


Fig. 12. Effects of biochar application on pesticide fate in soil (Reproduced from Khalid et al. [28], with permission from the publisher).

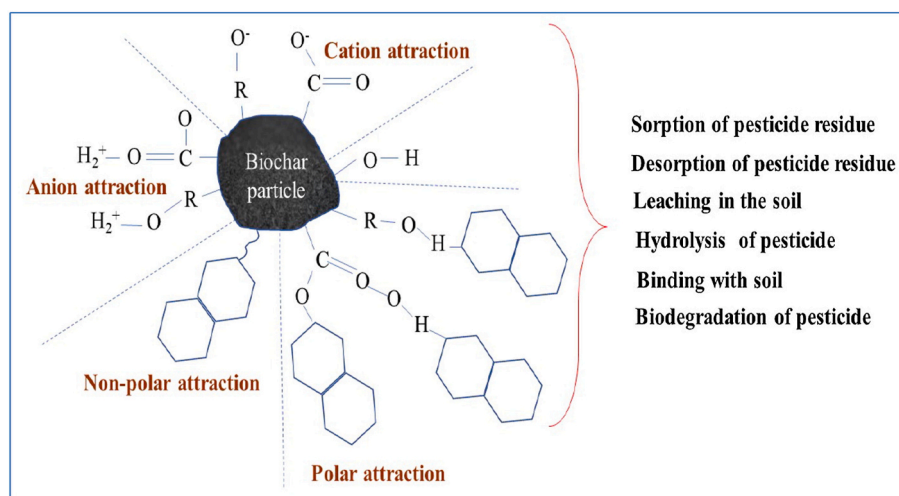


Fig. 13. Possible binding mechanisms of pesticides onto biochar and their effect on pesticide fate in soil (reproduced from Khalid et al. [28], with permission from the publisher).

Table 9

Summary of selected literature on the use of RHBC for construction and in building materials.

Materials used	Testing adopted	Outcome	Sources
Cement replacement from 0.1% to 0.75% of total volume of concrete with RHBC and recycled aggregate concrete.	ASTM C39 and ASTM C496 for compressive and splitting tensile strengths	RHBC at 0.1% produced highest compressive and splitting tensile strength with 17% and 3% increment respectively.	[247]
RHBC + mortar (sand, cement, water) + superplasticizer (0.36%–0.4%)	Compressive strength (testing protocol not mentioned); hydration kinetics and durability under chloride and sulfate environment	Addition of 2 wt% of RHBC led to improvement in mortar strength by 17%–24% compared to the control. Improvement in dimensional stability of mortar after exposure to sulfate.	[248]
RHBC both treated and untreated with super plasticizer of varied proportion + sand, cement, and water for mortar	Compressive strength (ASTM C109); flexural strength (ASTM C348); water permeability (ASTM C1403)	Addition of thermally treated RHBC increased the strength of mortar by 20% and 34% at early stage (after 7 days) and at matured age (after 120 days) compared to mortar with industrial rice husk char, respectively.	[249]
RHBC both treated separately with Mg, Ca and K solution and untreated with super plasticizer of varied proportion + sand, cement, and water for mortar	Compressive strength (ASTM C109) and splitting tensile strength (ASTM C496)	Addition of 5% RHBC resulted to the highest compressive strength compared to other concrete mixes and control concrete. Replacement of 5% (wt) of the cement with treated and untreated RHBC increased the tensile strength.	[250]

7. Economic feasibility

An analysis of the economic feasibility of RBC for use by the agro-environmental and construction industries is of great use. Currently,

the data in the available literature are not yet sufficient to allow for an analysis of the economic feasibility of RBC for construction applications. Vast quantities of rice biowastes are generated annually, and such abundant waste is a potential source of feedstock for RBC production. Environmentally friendly disposal of rice waste costs approximately US \$2183 per year. The production of RBC and its application in different sectors may therefore provide an alternative disposal solution. As discussed in previous sections, RBC has the potential to enhance crop yields and mitigate GHG emissions through carbon sequestration [251,252].

Biochar is undoubtedly cost-effective when compared with commercial fertilizers as the former remains for longer periods of time when applied to soil [253,254]. Fru et al. [255] investigated this issue based on a semi-participatory methodology to gain new insights into the assessment of the challenges and environmental and economic feasibility of RBC production and use. Results showed that farmers using RHBC enjoyed larger profits compared with the control, and the net benefits amounted to US\$1.44 million and a marginal rate of return of 33%. Additional revenue (35%) was gained for CO₂ offsets at US\$60. An economic analysis comparing the use RBC and fertilizer suggested that even if the cost benefit of RBC declined linearly to nil, a 50% savings in phosphorus fertilizers and 10% increase in wheat yields can be achieved without compromising long-term soil fertility. The combined use of RBC and chemical nutrients can promote soil fertility and plant yields with increasing net benefit and cost efficiency [256]. Economic viability and cost considerations are vital to the energy sector [257]. Several previous studies conducted cost-benefit analyses of using RBC to increase crop productivity, energy production, and carbon sequestration [254,256,258]. Based on such analyses, the use of RBC is expected to be socio-economically and environmentally feasible. However, the economic feasibility of using RBCs in the fertilizer and energy-production industries depends on the costs of pyrolysis and feedstock collection.

8. Barriers to biochar application in agriculture

Little relevant data about biochar application are available with respect to practical application in farms. Despite considerable research into possible biochar application as a soil amendment/fertilizer, its acceptance in agriculture is remains limited. To adopt and apply biochar in farmland will depend on farmers' willingness to embrace the technology. The key potential barriers to practical application of biochar in farmlands include the lack of policies, deficiency of economic feasibility, low awareness at farmer level, gaps between research and application, and a lack of application-specific standards [259,260].

To assess the potential for adoption of biochar by agricultural,

Latawiec et al. [261] surveyed farmers in Poland (n = 161). Their finding that only 27% of the producers were familiar with the term “biochar” shows a need to go beyond laboratory/field research and share information related to biochar with farmers directly. Farmers may also be engaged in participatory research to adopt and adjust biochar application to their needs. The situation may be more problematic in less-developed countries (e.g., in South Asia and Africa), where educational levels of farmers are relatively low [260]. For example, the practical application of biochar in Pakistan and India is limited. In fact, biochar is considered a soil amendment as it has never been adopted as a fertilizer in less-developed countries. Even economic feasibility analyses carried out in developed nations such as the UK and US have focused primarily on large-scale enterprises, which have reported economic and agronomic benefits. However, soil type, crop choice, and biochar application processes are vital to determining the economic balance [262]. Little economic feasibility data are available for small farms [263–265].

Approximately 43% of respondents in one study were not willing to apply biochar to their farms [261]. The most common constraints to adopting biochar in agricultural practices were linked with high cost of application. This implies a need for an in-depth analysis of the economic feasibility of biochar application compared with other fertilizers and soil amendments.

9. Conclusions and prospects

- Our review demonstrates that the production of biochar and compost from RB improves the physical and chemical characteristics of these raw materials and increases their adsorption capacity for organic and inorganic contaminants in soil and water.
- Biochar and compost derived from RB have a strong potential to improve soil quality and remove TEs and pesticides from soil and water. Using RB-derived biochar to treat degraded soils and contaminated water is a promising technology that can play a role in shifting agricultural practices from the use of traditional, ineffective, expensive, and problematically applicable materials to emerging cost-effective and easily applicable materials. In addition, using RB-derived biochar and compost to treat contaminated soil and water provides multiple benefits in the form of improved soil and environmental quality and livelihood security.
- There are considerable scientific opportunities to understand the sustainable use of rice feedstock products as promising low-cost and effective materials for the remediation and management of contaminated soils and water, as well as their potential application in the construction sector.
- We recommend the use of RB-derived biochar and compost in a wide range of agro-environmental applications as a simple, cost-effective, and environmentally friendly solution for the sustainable management of agricultural biowaste and contaminated water and soil, particularly in developing countries.
- Reusing RBC and RC as organic sources of macro- and micro-nutrients, soil amendments, and immobilizing agents for soil and water contaminants may enhance soil health and increase the quantity and quality of agricultural products. RBC and RC can be a sustainable management approach to low-fertility soils and contaminated soils and water and to help produce safe and clean food. These benefits can be expanded for achievement of SDGs 1 (no poverty), 2 (zero hunger), 3 (good health and well-being), 6 (clean water and sanitation), and 15 (life on land). RBC and RC have also been perceived in recent years as promising and effective options for carbon sequestration in agricultural soils, which contribute to the achievement of SDG 13 (climate action). The recent use of RBC in the construction industry may contribute to the achievement of SDG 9 (industry, innovation and infrastructure). Further analysis of the economic feasibility of RBC in the construction and agricultural industries may further enhance its cost-effective practical application.

Credit author statement

Sabry M. Shaheen: Creating the idea, visualization, investigation, collecting review of literature, creating tables and figures, and writing the original draft. **Vasileios Antoniadis:** Writing-review & editing, particularly sections 4.3, 4.4, 5.1, and 5.2. **Muhammad Shahid, Irshad Bibi, and Nabeel Niazi:** Writing-review & editing, particularly sections 2 and 3. **Yi Yang & Yiu Fai Tsang:** Writing-review & editing, particularly section 5.3. **Hamada Abdelrahman:** Writing-review & editing, particularly section 4.1 and 4.2. **Noha E. E. Hassan:** Creating tables and figures and listing the references. **Tao Zhang:** Writing-review & editing, particularly section 5.2. **Sherif A. Younis:** Revising & editing the entire article. **Mansour Almazroui:** Reviewing & editing the entire article. **Ajit K. Sarmah:** Writing-review & editing, particularly section 6. **Ki-Hyun Kim:** Visualization, writing, editing, and doing the proof reading of the entire article. **Jörg Rinklebe:** Visualization, supervision, writing-review & editing the entire article, and corresponding.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

KHK acknowledges support made by a grant from the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ITC (MSIT) of Korean government (Grant No: 2021R1A3B1068304).

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