Journal of Soils and Sediments
https://doi.org/10.1007/s11368-024-03927-2

SOILS, SEC 3 • REMEDIATION AND MANAGEMENT OF CONTAMINATED OR DEGRADED LANDS • REVIEW ARTICLE

Management of the soil environment using biochar and zeolite in various combinations: impact on soil condition and economical aspects

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Received: 13 February 2024 / Accepted: 29 October 2024
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Abstract

Purpose Both biochars (BCs) and zeolites (Zs) are defined as soil conditioners affecting various parameters of soil environment. In most cases, BCs and Zs are characterized by well-developed specific surface area, high porosity, and excellent sorption properties, which is highly helpful in soil reclamation or conditioning. This literature review compares impact of BCs and Zs on the physicochemical properties of various soils as well as economic aspects of their synthesis.

Materials and methods The review was prepared based on the articles published in the last 5 years (2018–2023). The articles were selected from the ScienceDirect® database using the keywords: 'biochar/zeolite impact on soil physicochemical properties', 'biochar/zeolite impact on water retention of soil' and 'biochar/zeolite economic aspects'.

Results and discussion Based on the available data, it can be stated that both BCs and Zs have good sorptive properties, which usually contributes to better growth of crops. Comparing them and choosing which one is more promising depends on the specific purpose and type of soil to which they are to be applied. BCs usage contributes mainly to providing organic matter and improving soil structure, while Zs enhance soil water retention. The profitability of BCs/Zs production depends largely on the precursor as well as the synthesis method.

Conclusions Due to the fact that impact of synthetic Zs on the soil environment is much less frequently investigated than that of BCs, the research using Zs and various soil types is especially needed. In some cases, it is advisable to apply biochar (BC) and zeolite (Z) simultaneously. Combinations of these materials may provide benefits in soil structure, water retention, and fertility. Such mixed techniques should be investigated in the near future.

Keywords Soil physicochemical properties · Water retention · Soil sorption complex · Soil aggregation · Economy

1 Introduction

Due to very slow pace of the soil-forming process, soil is almost non-renewable natural resource (Ferreira et al. 2022). 1 inch (2.54 cm) of topsoil needs about 500 years to be formed, but to develop 6 inches, that are most suitable to grow agricultural crops, even 3,000 years are required (Jeavons 2001). Soil is responsible for up to 95% of global food production. In addition, it plays a key role in protecting biodiversity, climate regulation, and maintaining the ecosystems health (Ferreira et al. 2022). Unfortunately, due to the unbalanced soil management practices, and climate changes, it was estimated that 36–75 billion tons of land are lost every year (Gobinath et al. 2022).

Soil degradation is caused by both anthropogenic activities and natural phenomena, and involves alteration of physical, chemical, or biological soil properties decreasing its fertility. It is classified as one of the most dangerous phenomena for the environment and society, currently observed in almost every region of the world. The most significant hazards include soil erosion, rising salinity, alterations in pH levels, desertification, soil sealing and compaction, reduction in humus and nutrient levels, and

Responsible editor: Jianming Xue

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pollution. All these phenomena reduce yields, deteriorate their quality, and even make them unfit for consumption (Delang 2018).

To limit soil degradation as well as remediate degraded soils, various soil additives are applied. In recent years, biochars (BCs) and zeolites (Zs) became the most popular amendments that significantly improve soil condition. Both materials can be obtained from various waste materials, which makes their production relatively cheap. Such a waste disposal complies with the principles of circular economy, sustainable development, and the zero-waste philosophy. Zs and BCs are safe to environment and organisms, and, owing to well-developed specific surface area and high porosity, they can sorb nutrients, water, or pollutants from various systems. So far, many positive effects of BCs and Zs on soil properties have been reported (Jarosz et al. 2022; Mondal et al. 2021; Murtaza et al. 2021; Szewczuk-Karpisz et al. 2024). But it is still not known which substances are more promising for degraded soils.

In this paper, the impact of BCs and Zs on the soils was compared and assessed. Their influence on the soil sorption complex, soil structure, water retention, and plant growth was described. What is more, the costs of using both materials for soil reclamation were evaluated. This review was prepared based on the articles published in the last 5 years (2018–2023). The works were selected from the ScienceDirect® database using the keywords: 'biochar/zeolite impact on soil physicochemical properties', 'biochar/zeolite impact on water retention of soil' and 'biochar/zeolite economic aspects'. As of February 8th, 2024, 6547 research papers were discovered using the keyword 'biochar impact on soil physicochemical properties', 6276 were found using 'biochar impact on water retention of soil', and 6326 were identified regarding the 'biochar economic aspects'. On the other hand, 2049 articles were found by the keyword 'synthetic zeolite impact on soil physicochemical properties', 1953, by 'synthetic zeolites impact on water retention of soil' and 4206, by 'synthetic zeolite economic aspects'. Until now, the issue of soil amendment with BCs and Zs has been studied by many researchers, but literature reports about BCs as soil additives are much more numerous than those about waste-derived Zs. Taking this into account, the authors also described the influence of natural Zs on individual soil properties. It is also worth mentioning that since 2018 there has been a 4.4-fold and 3.5-fold increase in the number of published works on soil reclamation by addition of BCs and Zs, respectively. In 2022, 2201 manuscripts on topic 'biochar soil remediation' were published, whilst in 2018, only 498. In 2022, 1086 manuscripts on topic 'zeolite soil remediation' were published, whilst in 2018, only 309. This means that this topic is of great interest.

2 Biochar

Biochar is a fine-grained, heterogeneous solid produced by biomass pyrolysis (Fig. 1), that is, thermochemical process, where organic materials break down without or with very small amounts of oxygen (Saletnik et al. 2019). The carbon-rich materials, which can be pyrolized to produce BC, are: various waste types (agricultural, forest, industrial, plastic, etc.), micro algae, marine and aquatic organisms (Weber and Quicker 2018). Depending on the type of starting material, BCs of various properties can be obtained. They differ in elemental composition, aromaticity, specific surface area, pH value, polarity, etc. (Xiao et al. 2018). In addition to pyrolysis, gasification, hydrothermal carbonization, microwave pyrolysis, flash carbonization, and torrefaction can be used to produce BC (Weber et al. 2018; Xiao et al. 2018; Yang et al. 2019). Appropriate selection of process parameters allows obtaining BCs with almost identical properties (Wang et al. 2020). BCs are usually characterized by unique features, i.e., neutral or alkaline pH, high specific surface area (even up to several hundred m^2/g), porous structure (even on the nanometer scale), and rich surface chemistry (high content of surface functional moieties). They are highly resistant to degradation and decomposition (Saletnik et al. 2019). Usually, the BC macropores create an environment for soil microorganisms, while the micropores take part in sorption of various substances (Lehmann et al. 2011).

BC application into the soil provides a broad spectrum of advantages, that is, soil structure improvement, increase in pH value, carbon sequestration, reduction in greenhouse gas emissions, increase in capacity of soil sorption complex. BC can act as a slow-release fertilizer and prevent the outflow of nutrients with rainwater. It can immobilize pollutants limiting their availability to organisms and preventing water eutrophication (Blackwell et al. 2012; Yang et al. 2019), as well as support composting and methane fermentation (Saletnik et al. 2019). BC amendment may also entail risks and prove to be unfavorable. It can be a source of harmful compounds like polycyclic aromatic hydrocarbons (PAH). Thus, the choice of precursor and pyrolysis temperature is crucial here. Plant-origin precursors have usually less contaminants than sewage sludges (Godlewska et al. 2021). Because of concerns on cost and safety, BC is typically applied in a relatively small quantity ($\leq 5\%$) (Wu and Bi 2019).

The way of BC application to the soils depends on their physicochemical properties (density, fineness), farming system, as well as available machinery/manpower. BCs added to topsoil are not dissoluted by rainfalls. As insoluble solids, they are usually introduced into topsoil mechanically (manually, with draft animals, or spreaders)

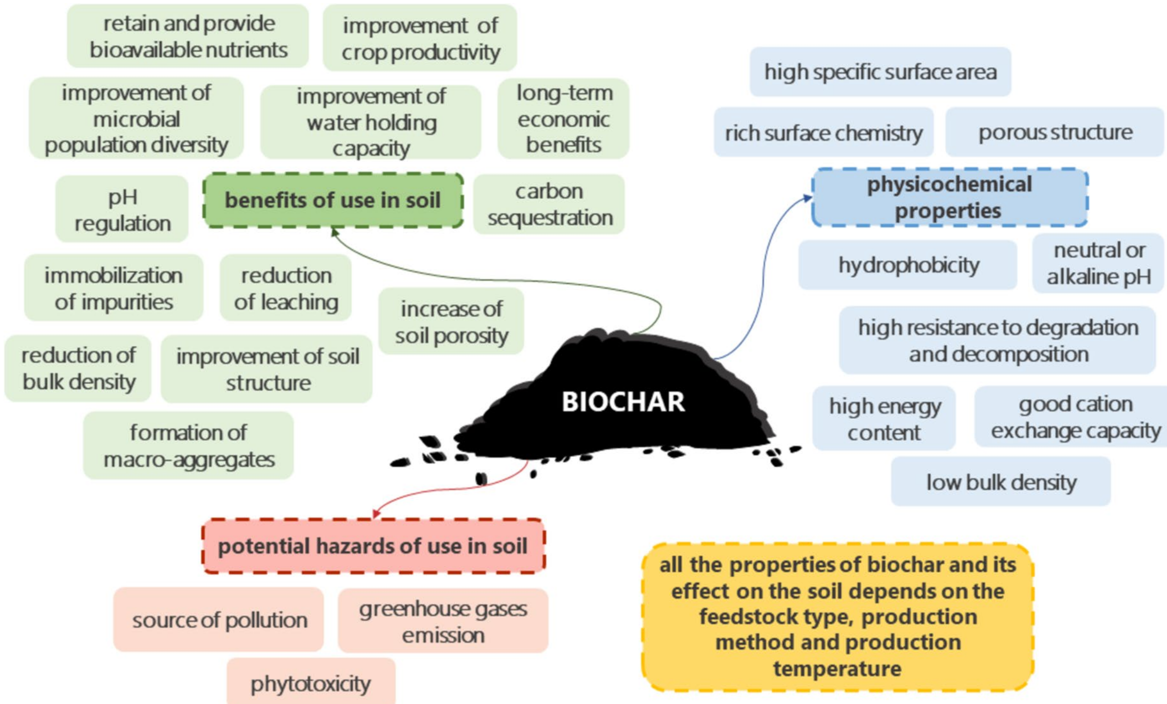

Fig. 1 Biochar properties and impact on soil condition

(Blackwell et al. 2012). Other methods of BC application, that is, broadcasting, furrow application, band application, deep banding, spot placement, were also described in the literature (Blackwell et al. 2012; Das et al. 2023). During uniform mixing with topsoil, a certain amounts of BC can be lost with wind. To avoid this problem, BC is incorporated in compost, manures, liquid manures, and slurries (Blackwell et al. 2012). The summary of BC properties and their impact on the soil are presented in Fig. 1.

2.1 Impact on water retention in soil

Soil water retention can be described by the water content at field capacity (FC), permanent wilting point (PWP) with their difference named available water content (AWC). FC refers to the moisture retained in soil once surplus gravitational water has drained off, and the speed of downward movement has diminished. Physically, it is bulk water content present in soil at -33 kPa of the suction pressure (Mitchell et al. 2022; Rai et al. 2017). PWP is a crucial threshold, when the roots are unable to extract sufficient moisture due to increase in the surface tension. At this juncture, water cannot permeate out of the soil as it strongly adheres to the soil particles (pressure head – 1500 kPa). AWC strongly depends on the soil structure (Mitchell et al. 2022; Rai et al. 2017). Figure 2 shows the scheme of soil water content at saturation, field capacity, and permanent wilting point. It was found that BC clearly affect soil moisture and water holding capacity (WHC). WHC, unlike FC, describes the total amount of water that the soil can maintain. It includes water held at FC and water in the pores (while completely saturated). BC addition increases soil water retention through positive effect on soil porosity and other structural and textural soil properties. Due to high porosity, BC usually increases water holding capacity of the soil, and BC pores provide additional space for water molecules (Alkharabsheh et al. 2021). The influence of waste-derived BCs on water retention of soil is compared in Table 1.

So far, it was noticed that the application of BC to sandy soil improved water retention, which was related to the change in soil porosity. Villagra-Mendoza and Horn (2018) observed that the addition of mango wood-derived BC (obtained at 600 ℃) increased water retention of coarse-textured sandy soil. Pore size distribution (PSD) in the sandy substrate changed significantly, that is, the fraction of wide, coarse pores was reduced, whereas mesoporosity was increased. Through repeated wetting and drying cycles, the structural stability of the pore system was improved, which resulted in higher saturated hydraulic conductivity. The BC addition enhanced soil rigidity, especially in sandy mixtures, by creating an internal pore structure resistant to hydraulic deformation caused by drying. This proved that BC was well-suited to mitigate extreme hydrological conditions. For sandy soils, the available water increased significantly with higher BC dosage, while for sandy loam soils, significant

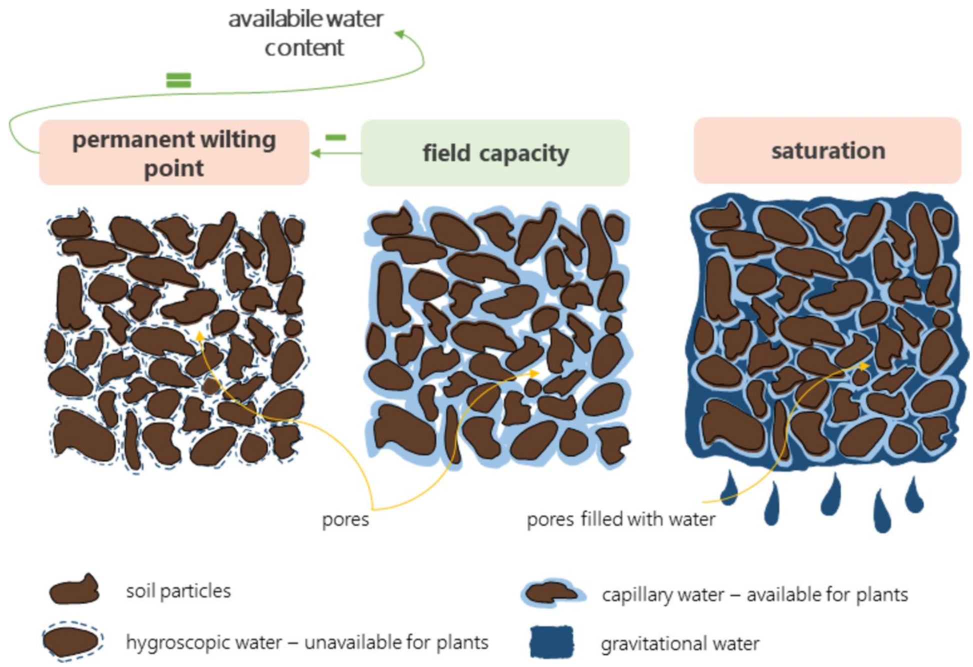

Fig. 2 Soil water content at saturation, field capacity and permanent wilting point (prepared based on Datta et al. (2017))

differences were observed only between the control and the 5% BC treatment.

Several studies indicated that BC reduced soil bulk density, but increased soil porosity. This improvement in soil structure enhanced both hydraulic conductivity and water retention. Zhou et al. (2019) observed that maize cobs-derived BC in 9 t ha^{-1} (HB) dose improved water retention of soil (including gravitational, capillary, and hygroscopic ones). The dose of 4.5 t ha^{-1} (LB) did not bring similar results, however, both doses increased plant-available water content by 17.8% (HB) and 10.1% (LB), respectively, in sandy loam soil. Edeh et al. (2020) in his meta-analysis concluded that BCs have a positive impact on soil water retention of sandy soils, which was dictated by decreased saturated hydraulic conductivity. In contrast, Toková et al. (2020) examined BC-amended Haplic Luvisol and observed that saturated hydraulic conductivity (K_{sat}) did not change after BC application of 10 t ha^{-1}, but the addition of 20 t ha^{-1} changed it significantly from 2.12 to 11.96 cm h^{-1}. BC used in the experiments was obtained from the mixture of paper fiber sludge and grain husks at 550 ℃ for 30 min. Ghorbani et al. (2022) noted that sandy loam FC increased by 29% and 47%, and K_{sat} increased 104% and 145% after the addition of 5 and 10 t ha^{-1} of rice straw BC (produced at 500 ℃), respectively. AWC was also improved by 76% and 48% due to increasing contents of micro- and mesopores.

2.2 Impact on soil structure

Soil structure involves the clustering of soil ingredients (sand, silt, clay, organic matter) into porous formations known as aggregates. It also applies to the organization of these aggregates creating granular, blocky, prismatic, and massive structures (Fig. 3). When massive structure dominates the topsoil, it impedes water and air penetration making seed germination difficult. Conversely, when the topsoil exhibits a granular structure, water infiltration is facilitated, and seed germination is improved (Rai et al. 2017).

BC possesses the capability to alter soil structure (Azeem et al. 2021). It can decrease soil compaction and enhance soil porosity, which gives beneficial effect on soil microbial community and nutrient cycling (Alkharabsheh et al. 2021). However, in some cases, BC has no or negative effect on physical properties of soil. For example, the decrease in structural stability of clay soil was observed after the straw BC addition (Zhou et al. 2019). The effects of waste-derived BCs on soil structure are summarized in Table 2.

2.2.1 Bulk density

Bulk density (BD) offers insights into the volume of pores within the soil. It allows to assess soil compaction and aeration, which influences water infiltration, movement of nutrients, and rooting depth of plants (Alkharabsheh et al. 2021). The lower bulk density, the better soil structure is noted (Zhang et al. 2021). Figure 4 schematically shows influence of BD on soil porosity.

In most cases, the BC application reduced BD of the soil. Adekiya et al. (2019) performed 2-year experiments using BC prepared from hardwood (such as *Parkis biglosa*, *Khaya senegalensis*, *Prosopis Africana,* and *Terminalia glaucescens*) at 580 °C in 24 h. The soil used in the study

Table 1 Impact of biochars and zeolites on water retention of soils

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/ Effect Before amendment	After amendment	Difference	Reference
Biochar							
Saturated hydraulic conductivity	maize-cob, 360 °C	4.5 t ha^{-1}	Fluvic Cambisol (sandy loam soil)	0.78 cm $hour^{-1}$	0.59 cm $hour^{-1}$	-0.19	Zhou et al. 2019
		9.0 t ha^{-1}			1.61 cm $hour^{-1}$	0.83	
	mixture of paper fiber sludge and grain husks, 550 °C	10 t ha^{-1}	Haplic Luvisol (silty loam)	2.12 cm h^{-1}	10.73 cm h^{-1}	9.61	Toková et al. 2020
		20 t ha^{-1}			9.97 cm h^{-1}	7.85	
	grape stalks, 600 °C	2%	Fluvisol (sandy loam)	decrease			Jačka et al. 2018
		5%		more significant decrease			
Field water-holding capacity	rice straw, 550 °C	11.25 ha^{-1}	paddy soil	34.42 cm^3 cm^{-3}	35.47 cm^3 cm^{-3}	1.05	Yang et al. 2021
		22.5 t ha^{-1}			35.83 cm^3 cm^{-3}	1.41	
	maize straw, 550 °C	11.25 ha^{-1}			35.91 cm^3 cm^{-3}	1.49	
		22.5 t ha^{-1}			35.90 cm^3 cm^{-3}	1.48	
	wheat straw, 550 °C	11.25 ha^{-1}			36.19 cm^3 cm^{-3}	1.77	
		22.5 t ha^{-1}			36.89 cm^3 cm^{-3}	2.47	
	eice husk, 550 °C	11.25 ha^{-1}			35.75 cm^3 cm^{-3}	1.37	
		22.5 t ha^{-1}			38.32 cm^3 cm^{-3}	3.9	
	bamboo, 550 °C	11.25 ha^{-1}			37.20 cm^3 cm^{-3}	2.78	
		22.5 t ha^{-1}			37.82 cm^3 cm^{-3}	3.40	
	waste acaí seeds from fruit processing, maximum 450 °C, average 300 °C	20 g kg^{-1}	Yellow Latosol (sandy loam)	0.206 kg kg^{-1}	0.191 kg kg^{-1}	-0.015	Sato et al. 2020
		40 g kg^{-1}			0.187 kg kg^{-1}	-0.019	
		60 g kg^{-1}			0.191 kg kg^{-1}	-0.015	
		20 g kg^{-1}	Yellow Latosol (clay)	0.287 kg kg^{-1}	0.295 kg kg^{-1}	0.008	
		40 g kg^{-1}			0.275 kg kg^{-1}	-0.008	
		60 g kg^{-1}			0.286 kg kg^{-1}	-0.001	
	fruit branch of Palmetto, 500–600 °C	10 t ha^{-1}	silt clay loam and sand	0.278 cm^3 cm^{-3}	0.390 cm^3 cm^{-3}	0.112	Liang et al. 2021
		25 t ha^{-1}			0.408 cm^3 cm^{-3}	0.130	
		50 t ha^{-1}			0.375 cm^3 cm^{-3}	0.097	
		100 t ha^{-1}			0.368 cm^3 cm^{-3}	0.090	

Table 1 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/ Effect Before amendment	After amendment	Difference	Reference
Plant available water content	maize-cob, 360 °C	4.5 t ha^{-1}	Fluvic Cambisol (sandy loam soil)	0.101	0.116	0.015	Zhou et al. 2019
		9.0 t ha^{-1}			0.123	0.022	
	mixture of paper fiber sludge and grain husks, 550 °C	10 t ha^{-1} (reapplication)	Haplic Luvisol (silty loam)	4.03% vol	5.52% vol	1.49	Toková et al. 2020
		20 t ha^{-1} (reapplication)			6.65% vol	2.62	
	rice straw, 550 °C	11.25 ha^{-1}	paddy soil	4.20 cm^3 cm^{-3}	4.59 cm^3 cm^{-3}	0.39	Yang et al. 2021
		22.5 t ha^{-1}			4.85 cm^3 cm^{-3}	0.65	
	maize straw, 550 °C	11.25 ha^{-1}			5.13 cm^3 cm^{-3}	0.93	
		22.5 t ha^{-1}			4.92 cm^3 cm^{-3}	0.72	
	wheat straw, 550 °C	11.25 ha^{-1}			5.20 cm^3 cm^{-3}	1.00	
		22.5 t ha^{-1}			5.31 cm^3 cm^{-3}	1.11	
	rice husk, 550 °C	11.25 ha^{-1}			4.75 cm^3 cm^{-3}	0.55	
		22.5 t ha^{-1}			5.98 cm^3 cm^{-3}	1.78	
	bamboo, 550 °C	11.25 ha^{-1}			5.09 cm^3 cm^{-3}	0.89	
		22.5 t ha^{-1}			4.84 cm^3 cm^{-3}	0.64	
	waste acaí seeds from fruit processing, maximum 450 °C, average 300 °C	20 g kg^{-1}	Yellow Latosol (sandy loam)	0.098	0.087	-0.011	Sato et al. 2020
		40 g kg^{-1}			0.083	-0.015	
		60 g kg^{-1}			0.091	-0.007	
		20 g kg^{-1}	Yellow Latosol (clay)	0.064	0.072	0.008	
		40 g kg^{-1}			0.072	0.008	
		60 g kg^{-1}			0.074	0.010	
	fruit branch of Palmetto, 500–600 °C	10 t ha^{-1}	silt clay loam and sand	0.177 cm^3 cm^{-3}	0.196 cm^3 cm^{-3}	0.019	Liang et al. 2021
		25 t ha^{-1}			0.206 cm^3 cm^{-3}	0.029	
		50 t ha^{-1}			0.172 cm^3 cm^{-3}	-0.005	
		100 t ha^{-1}			0.163 cm^3 cm^{-3}	-0.014	

Table 1 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/ Effect Before amendment	After amendment	Difference	Reference
Permanent wilting point	maize-cob, 360 °C	4.5 t ha^{-1}	Fluvic Cambisol (sandy loam soil)	0.100	0.108	0.008	Zhou et al. 2019
		9.0 t ha^{-1}			0.113	0.013	
	mixture of paper fiber sludge and grain husks, 550 °C	10 t ha^{-1} (reapplication)	Haplic Luvisol (silty loam)	25.79% vol	24.14% vol	-1.65	Toková et al. 2020
		20 t ha^{-1} (reapplication)			23.74% vol	-2.05	
	rice straw, 550 °C	11.25 ha^{-1}	paddy soil	30.22 cm^3 cm^{-3}	30.88 cm^3 cm^{-3}	0.66	Yang et al. 2021
		22.5 t ha^{-1}			30.98 cm^3 cm^{-3}	0.76	
	maize straw, 550 °C	11.25 ha^{-1}			30.78 cm^3 cm^{-3}	0.56	
		22.5 t ha^{-1}			30.98 cm^3 cm^{-3}	0.76	
	wheat straw, 550 °C	11.25 ha^{-1}			30.99 cm^3 cm^{-3}	0.77	
		22.5 t ha^{-1}			31.58 cm^3 cm^{-3}	1.36	
	rice husk, 550 °C	11.25 ha^{-1}			31.00 cm^3 cm^{-3}	0.78	
		22.5 t ha^{-1}			32.35 cm^3 cm^{-3}	2.13	
	bamboo, 550 °C	11.25 ha^{-1}			32.11 cm^3 cm^{-3}	1.89	
		22.5 t ha^{-1}			32.98 cm^3 cm^{-3}	2.76	
	waste acaí seeds from fruit processing, maximum 450 °C, average 300 °C	20 g kg^{-1}	Yellow Latosol (sandy loam)	0.110	0.104	-0.006	Sato et al. 2020
		40 g kg^{-1}			0.104	-0.006	
		60 g kg^{-1}			0.100	-0.01	
		20 g kg^{-1}	Yellow Latosol (clay)	0.223	0.223	0.000	
		40 g kg^{-1}			0.203	-0.02	
		60 g kg^{-1}			0.212	-0.009	
	fruit branch of Palmetto, 500–600 °C	10 t ha^{-1}	silt clay loam and sand	0.101 cm^3 cm^{-3}	0.104 cm^3 cm^{-3}	0.003	Liang et al. 2021
		25 t ha^{-1}			0.108 cm^3 cm^{-3}	0.007	
		50 t ha^{-1}			0.095 cm^3 cm^{-3}	-0.006	
		100 t ha^{-1}			0.090 cm^3 cm^{-3}	-0.011	
Zeolites							

Table 1 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/ Effect Before amendment	After amendment	Difference	Reference
Saturated hydraulic conductivity	coal fly ash converted by pre-fusion hydrothermal process at 60℃ and Ca-exchanged	1, 2, 5, 10% (which corresponds to 0.5–5 t/ha)	Eutric Cambisols (sandy loam)	an increasingly greater decrease (58–70%) as the dose increases in range			Comegna et al. 2023
			Eutric Vertisols (sandy loam)	an increasingly greater decrease (in range 63–75%) as the dose increases			
			Luvic Kastanozems (sandy loam)	an increasingly greater decrease (in range 7–67%) as the dose increases			
			Epileptic Phaeozems (silty loam)	an increasingly greater decrease (in range 20–94%) as the dose increases			
	clinoptilolite	2%	Typic Calcixerolic Xerochrept (sandy loam soil)	0.49 cm min^{-1}	0.37	-0.12	Mazloomi and Jalali 2019
		4%			0.38	-0.11	
		8%			0.21	-0.28	
	ash converted by pre-fusion hydrothermal process at 60℃ and Ca-exchanged	1%	Epileptic Phaeozems (silty loam)	0.056 cm min^{-1}	0.045	-0.009	Belviso et al. 2022
		2%			0.028	-0.031	
		5%			0.0079	-0.0481	
		10%			0.0032	-0.0528	

Table 1 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/ Effect Before amendment	After amendment	Difference	Reference
Available water content	coal fly ash converted by pre-fusion hydrothermal process at 60°C and Ca-exchanged	1%	Eutric Cambisols (sandy loam)	0.133 cm^3/cm^3	0.129	-0.004	Comegna et al. 2023
		2%			0.177	0.044	
		5%			0.138	0.005	
		10%			0.167	0.034	
		1%	Eutric Vertisols (sandy loam)	0.149 cm^3/cm^3	0.201	0.052	
		2%			0.198	0.049	
		5%			0.303	0.154	
		10%			0.226	0.077	
		1%	Luvic Kastanozems (sandy loam)	0.168 cm^3/cm^3	0.170	0.002	
		2%			0.185	0.017	
		5%			0.182	0.014	
		10%			0.218	0.05	
		1%	Epileptic Phaeozems (silty loam)	0.150 cm^3/cm^3	0.145	-0.005	
		2%			0.159	0.009	
		5%			0 142	-0.008	
		10%			0 137	-0.013	
	clinoptilolitic tuff	8 t/ha (~0.35%), field experiment	acidic brown soil	no effect of the added zeolite on available water content			Szatanik-Kloc et al. 2021
		40 t/ha, laboratory study		9.48%	13.1%	3.62	

Table 1 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/ Effect Before amendment	After amendment	Difference	Reference
Water content at field capacity	coal fly ash converted by pre-fusion hydrothermal process at 60°C and Ca-exchanged	1%	Eutric Cambisols (sandy loam)	0.293 cm^3/cm^3	0.322	0.029	Comegna et al. 2023
		2%			0.335	0.042	
		5%			0.368	0.075	
		10%			0.428	0.135	
		1%	Eutric Vertisols (sandy loam)	0.319 cm^3/cm^3	0.346	0.027	
		2%			0.355	0.036	
		5%			0.435	0.116	
		10%			0.485	0.166	
		1%	Luvic Kastanozems (sandy loam)	0.296 cm^3/cm^3	0.323	0.027	
		2%			0.352	0.056	
		5%			0.408	0.112	
		10%			0.473	0.177	
		1%	Epileptic Phaeozems (silty loam)	0.379 cm^3/cm^3	0.417	0.038	
		2%			0.419	0.040	
		5%			0.504	0.125	
		10%			0.593	0.214	

Table 1 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/ Effect Before amendment	After amendment	Difference	Reference
Water content at permanent wilting point	coal fly ash converted by pre-fusion hydrothermal process at 60℃ and Ca-exchanged	1%	Eutric Cambisols (sandy loam)	0.160 cm^3/cm^3	0.193	0.033	Comegna et al. 2023
		2%			0.158	-0.002	
		5%			0.230	0.070	
		10%			0.261	0.101	
		1%	Eutric Vertisols (sandy loam)	0.170	0.145	-0.025	
		2%			0.157	-0.013	
		5%			0.132	-0.038	
		10%			0.259	0.089	
		1%	Luvic Kastanozems (sandy loam)	0.128	0.153	0.025	
		2%			0.167	0.039	
		5%			0.226	0.098	
		10%			0.255	0.0127	
		1%	Epileptic Phaeozems (silty loam)	0.255	0.272	0.017	
		2%			0.260	0.005	
		5%			0.362	0.107	
		10%			0.456	0.201	
Water holding capacity	Zeolite	2.5 t ha^{-1}	red sandy loam	33.34%	38.61%	5.27	Ravali et al. 2020
		5 t ha^{-1}			42.61%	9.27	
		7.5 t ha^{-1}			48.54%	15.20	

All percent doses were 'w/w'

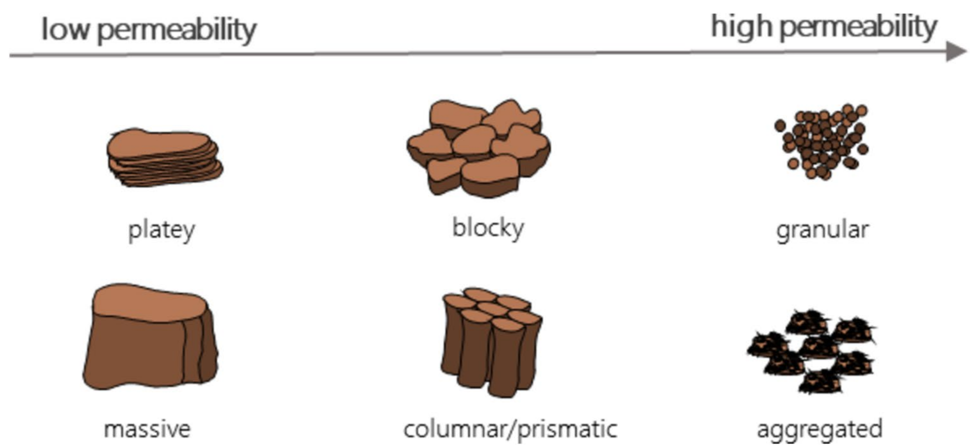

Fig. 3 Impact of soil structure on permeability of soil (prepared based on Haering et al. (2015))

was Alfisol (classified as Oxic Haplustalf) and Luvisol. The applied BC doses, i.e., 25 and 50 t ha^{-1}, reduced soil bulk density from 1.49 Mg m^{-3} in the first year, to 1.29 and 1.17, respectively, in the second year. BC-amended soil had reduced bulk density due to dilution effect – BC was characterized by lower bulk density than the soil. Toková et al. (2020) performed the experiment, in which BC (obtained from the mixture of paper fiber sludge and grain husks at 550 ℃ in 30 min) was re-applied to Haplic Luvisol in doses of 10 and 20 t ha^{-1} after 4 years of experiment. The significant decrease in BD was only observed for application (from 1.41 to 1.36 g cm^{-3}) and re-application (from 1.41 to 1.25 g cm^{-3}) at a dose of 20 t ha^{-1} of BC as well as for re-application (1.41 to 1.24 g cm^{-3}) at the dose of 10 t ha^{-1}. The BC application at the dose of 10 t ha^{-1} had no significant effect on BD. Similar results were obtained by Zhou et al. (2019), but BC doses that they applied were significantly lower. The 4.5 t ha^{-1} dose decreased BD from 1.27 to 1.22, whereas the 9.0 t ha^{-1} dose, to 1.13 g cm^{-3}. In this case, sandy loam soil (Fluvic Cambisol) and maize-cob-derived BC were used for the study. Ghorbani et al. (2022) added BC (rice straw-derived, obtained at 500 ℃) at 5 and 10 t ha^{-1} dose to sandy loam soil. Both doses resulted in the BD decrease. For 5 t ha^{-1}, it was 1.33 g cm^{-3}, whereas for 10 t ha^{-1}, 1.21 g cm^{-3}, comparing to 1.42 g cm^{-3} observed for the control.

2.2.2 Aggregation

A key aspect of soil structure is aggregate stability, which refers to their ability to withstand disintegration when subjected to disruptive external forces. Soil micro-aggregates are formed through various bonding mechanisms occurring between minerals and organic molecules. When micro-aggregates are developing, they combine to form macroaggregates, binding to soil organic matter (SOM), clay, and cations (Murtaza et al. 2021). The stability of soil aggregates is significantly influenced by various soil internal forces (SIFs), such as electrostatic, hydration, and van der Waals ones (Hu et al. 2021). Macro- and microaggregates composition is presented in Fig. 5.

The BC addition proved to enhance soil aggregation leading to improved soil quality and fertility. This is associated with formation of macro-aggregates, which makes soil stability higher and reduces erosion risk. Macro-aggregate formation increases water infiltration and nutrient availability for plants (Murtaza et al. 2021). Zhou et al. (2019) conducted 8-year field trial and investigated the effects of successive additions of high (9.0 t ha^{-1}) and low (4.5 t ha^{-1}) doses of maize-cob-derived BC to sandy loam soil. However, they did not observed higher content of macroaggregates or improved aggregate stability. It was probably dictated by inappropriate BC type.

Ghorbani et al. (2022) measured mean weight diameter (MWD) of sandy loam after addition of 5 and 10 t ha^{-1} dose of BC (rice straw-derived, obtained at 500℃). They noted the increase in MWD equaled to 79% and 166%, respectively, comparing to the control. This indicated that BC was able to improve plants ventilation and provided soil structure better for crops.

Aggregate tensile strength (Q) is a parameter describing the stability of the soil structure. It appropriate values promote long-term crop productivity of the soil by sustaining gas diffusion, aiding root penetration, enhancing water infiltration, and seedling emergence (Sokołowska et al. 2020). Sokołowska et al. (2020) performed studies on tensile strength of unfractionated and fractionated (1–0.25, 0.25–0.1, 0.1–0.05, and < 0.05 mm) artificial cylindrical aggregates of degraded Dystric Cambisol. They investigated wetted and air-dried aggregates with and without BCs (obtained from wood waste or sunflower husk), at 0.1 or 5% dose. The air-dried aggregates had generally higher Q than wetted ones, which was linked to the dehydration of soil gels and heat-induced alteration of iron and alumina oxides as the soil undergoes drying. The BC addition, regardless of

Table 2 Impact of biochars and zeolites on soil structure

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/Effect		Difference	Reference
				Before amendment	After amendment		
Biochar							
Total porosity	maize-cob, 360 °C	4.5 t ha^{-1}	Fluvic Cambisol (sandy loam soil)	0.52 cm^3cm^{-3}	0.53 cm^3cm^{-3}	0.01	Zhou et al. 2019
		9.0 t ha^{-1}			0.56 cm^3cm^{-3}	0.04	
	waste acaí seeds from fruit processing, maximum 450 °C, average 300 °C	20 g kg^{-1}	Yellow Latosol (sandy loam)	0.413 m^3m^{-3}	0.364 m^3m^{-3}	-0.049	Sato et al. 2020
		40 g kg^{-1}			0.354 m^3m^{-3}	-0.059	
		60 g kg^{-1}			0.322 m^3m^{-3}	-0.091	
		20 g kg^{-1}	Yellow Latosol (clay)	0.389 m^3m^{-3}	0.389 m^3m^{-3}	0.000	
		40 g kg^{-1}			0.364 m^3m^{-3}	-0.025	
		60 g kg^{-1}			0.417 m^3m^{-3}	0.028	
	corn residue, 350 °C	1%	Typic Torriorthents (sandy loam soil)	0.373 cm^3 cm^{-3}	0.401 cm^3 cm^{-3}	0.028	Saffari et al. 2021
		2%			0.479 cm^3 cm^{-3}	0.106	
		4%			0.508 cm^3 cm^{-3}	0.135	
	corn residue, 650 °C	1%			0.407 cm^3 cm^{-3}	0.034	
		2%			0.465 cm^3 cm^{-3}	0.092	
		4%			0.502 cm^3 cm^{-3}	0.219	
Mechanical stability of aggregates (aggregate destruction percentage)	created in a factory-scale reactor, 500–550 °C	30 g kg^{-1}	Vertisol	24.14%	40.44%	16.3	Cai et al. 2022
	rice straw, 550 °C	11.25 t ha^{-1}	paddy soil	32.9% (aggregate destruction percentage)	25.0%	-7.9	Yang et al. 2021
		22.5 t ha^{-1}			22.2%	-10.7	
	maize straw, 550 °C	11.25 t ha^{-1}			30.2%	-2.7	
		22.5 t ha^{-1}			19.1%	-13.8	
	wheat straw, 550 °C	11.25 t ha^{-1}			26.9%	-6	
		22.5 t ha^{-1}			24.7%	-8.2	
	rice husk, 550 °C	11.25 t ha^{-1}			32.8%	-0.1	
		22.5 t ha^{-1}			23.4%	-9.5	
	bamboo, 550 °C	11.25 t ha^{-1}			24.1%	-8.8	
		22.5 t ha^{-1}			20.1%	-12.8	

Table 2 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/Effect		Difference	Reference
				Before amendment	After amendment		
Water stability of aggregates	leaves of the date palm, 400–450 °C	1%	Torripsamments (calcareous loamy sand soil)	76.35%	increase by 24.56%		Ibrahim et al. 2021
		2%			increase by 28.92%		
		3%			increase by 29.59%		
		4%			increase by 30.97%		
		1%	Torripsamments (calcareous loamy sand soil), macro-aggregates > 0.25 mm	15.94%	increase by 69.93%		
		2%			increase by 89.54%		
		3%			increase by 111.4%		
		4%			increase by 164.2%		
	maize-cob, 360 °C	4.5, 9.0 t ha^{-1}	Fluvic Cambisol (sandy loam soil) 0.25–2 mm fraction	no significant difference			Zhou et al. 2019
	created in a factory-scale reactor, 500–550 °C	30 g kg^{-1}	Vertisol, macroaggregates of 2–0.25 mm	significantly increased			Cai et al. 2022
			Vertisol, microaggregates of < 0.053 mm	significantly decreased			
Mean weight diameter	straw, 500–600 °C	1 t ha^{-1}	sandy loam 0–20 cm depth	0.61 mm	0.84 mm	0.23	Bai et al. 2019
			sandy loam 20–40 cm depth	0.38 mm	0.60 mm	0.22	
	leaves of the date palm, 400–450 °C	1%	Torripsamments (calcareous loamy sand soil)	0.19 mm	increased by 57.46%		Ibrahim et al. 2021
		2%			increased by 71.30%		
		3%			increased by 85.24%		
		4%			increased by 121.60%		
	maize-cob, 360 °C	4.5 t ha^{-1}, 9.0 t ha^{-1}	Fluvic Cambisol (sandy loam soil)	0.195 mm	2.235 – 0.247 mm		Zhou et al. 2019

Table 2 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/Effect		Difference	Reference
				Before amendment	After amendment		
Bulk density	waste acaí seeds from fruit processing, maximum 450 °C, average 300 °C	20 g kg^{-1}	Yellow Latosol (sandy loam)	1.560 Mg m^{-3}	1.456 Mg m^{-3}	-0.104	Sato et al. 2020
		40 g kg^{-1}			1.461 Mg m^{-3}	-0.099	
		60 g kg^{-1}			1.424 Mg m^{-3}	-0.136	
		20 g kg^{-1}	Yellow Latosol (clay)	0.991	0.998 Mg m^{-3}	0.007	
		40 g kg^{-1}			0.962 Mg m^{-3}	-0.029	
		60 g kg^{-1}			1.090 Mg m^{-3}	0.099	
	maize-cob, 360 °C	4.5 t ha^{-1}	Fluvic Cambisol (sandy loam soil)	1.27 g cm^{-3}	1.22 g cm^{-3}	-0.05	Zhou et al. 2019
		9.0 t ha^{-1}			1.13 g cm^{-3}	0.14	
	mixture of paper fiber sludge and grain husks 550 °C	10 t ha^{-1}	Haplic Luvisol (silty loam)	1.41 g cm^{-3}	1.39 g cm^{-3}	-0.02	Toková et al. 2020
		10 t ha^{-1} (after reapplication)			1.24 g cm^{-3}	-0.17	
		20 t ha^{-1}			1.36 g cm^{-3}	-0.05	
		20 t ha^{-1} (after reapplication)			1.25 g cm^{-3}	-0.16	
	corn residue, 350 °C	1%	Typic Torriorthents (sandy loam soil)	1.66 Mg m^{-3}	1.59 Mg m^{-3}	-0.07	Saffari et al. 2021
		2%			1.38 Mg m^{-3}	-0.28	
		4%			1.30 Mg m^{-3}	-0.36	
	corn residue, 650 °C	1%			1.57 Mg m^{-3}	-0.09	
		2%			1.42 Mg m^{-3}	-0.24	
		4%			1.32 Mg m^{-3}	-0.34	
Zeolites							
Pore size	clinoptilolite zeolite (particle size 20, 2 and 0.2 μm)	1%	Calcaric Arenosols (loamy sand)	141.6 Å	129.1, 128.9, 123.7 Å, respectively		Ibrahim et al. 2021
Mean weight diameter	natural zeolite (anzimit)	5 g kg^{-1}	sandy loam	697.14% increase comparing to the control			Amirahmadi et al. 2022
		10 g kg^{-1}		274.29% increase comparing to control			

Table 2 (continued)

Parameter	Amendment type	Amendment dose	Soil type	Parameter value/Effect		Difference	Reference
				Before amendment	After amendment		
Specific surface area	clinoptilolitic tuff	8 t/ha (~0.35%), field experiment	acidic brown soil	no effect of the added zeolite on specific surface area			Szatanik-Kloc et al. 2021
	clinoptilolite (particle size 20, 2 and 0.2 µm)	1%	Calcaric Arenosols (loamy sand)	3.559 $m^2\ g^{-1}$	34.722, 35.001, 37.296 $m^2\ g^{-1}$, respectively		Ibrahim and Alghamdi 2021
Bulk density	zeolite	2.5 $t\ ha^{-1}$	red sandy loam	1.15 $Mg\ m^{-3}$	1.11 $Mg\ m^{-3}$	-0.04	Ravali et al. 2020
		5 $t\ ha^{-1}$			0.99 $Mg\ m^{-3}$	-0.16	
		7.5 $t\ ha^{-1}$			0.98 $Mg\ m^{-3}$	-0.17	
	clinoptilolite	2%	Typic Calcixerolic Xerochrept (sandy loam soil)	1.44 g/cm^3	No changes in bulk density		Mazloomi and Jalali 2019
		4%					
		8%					

All percent doses were 'w/w'

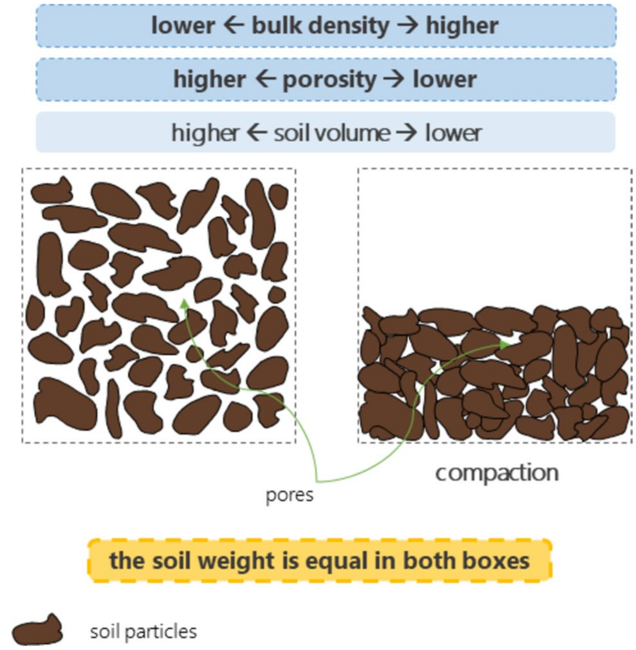

Fig. 4 Bulk density and its impact on soil porosity (prepared based on DeJong-Hughes and Daigh (2022))

its type, reduced the Q parameter of all examined samples, which was mainly caused by the formation of macropores. Reduction in Q was more significant for the higher doses. What is more, the most significant decrease (by 0.048 MPa) was noted when sunflower husks BC at 5% dose was applied for the wetted fraction of 1–0.25 mm.

2.2.3 Porosity

Porosity refers to the empty spaces or pores between soil particles (minerals and solid organic matter) filled with air or water. It varies depending on soil texture, e.g., clayey soils have the highest porosity, whereas sandy soils, the lowest one.

In some cases, BC application enhances soil porosity (Alkharabsheh et al. 2021, Alghamdi et al. 2018), which improves air, water, and heat movement. Adequate aeration and drainage are crucial for root growth, as they provide oxygen to them and prevent waterlogging (Hossain et al. 2020). The BC addition can also reorganize soil pores (Villagra-Mendoza and Horn 2018). Zhou et al. (2019) observed increased total- and macroporosity of sandy loam soil. Previously mentioned experiment of Adekiya et al. (2019) showed also increase in porosity after 2-year experiment, from 43.8% to 51% and 55.8% for 25 and 50 $t\ ha^{-1}$ doses, respectively. Toková et al. (2020) noticed the 13% increase in Haplic Luvisol porosity, from 44.19 to 49.98%, when it was amended with BC dose of 10 $t\ ha^{-1}$. The higher dosage (20 $t\ ha^{-1}$) did not cause additional increase in the porosity, i.e., it stayed at the level of 49.37%. The results were obtained after re-application of BC to

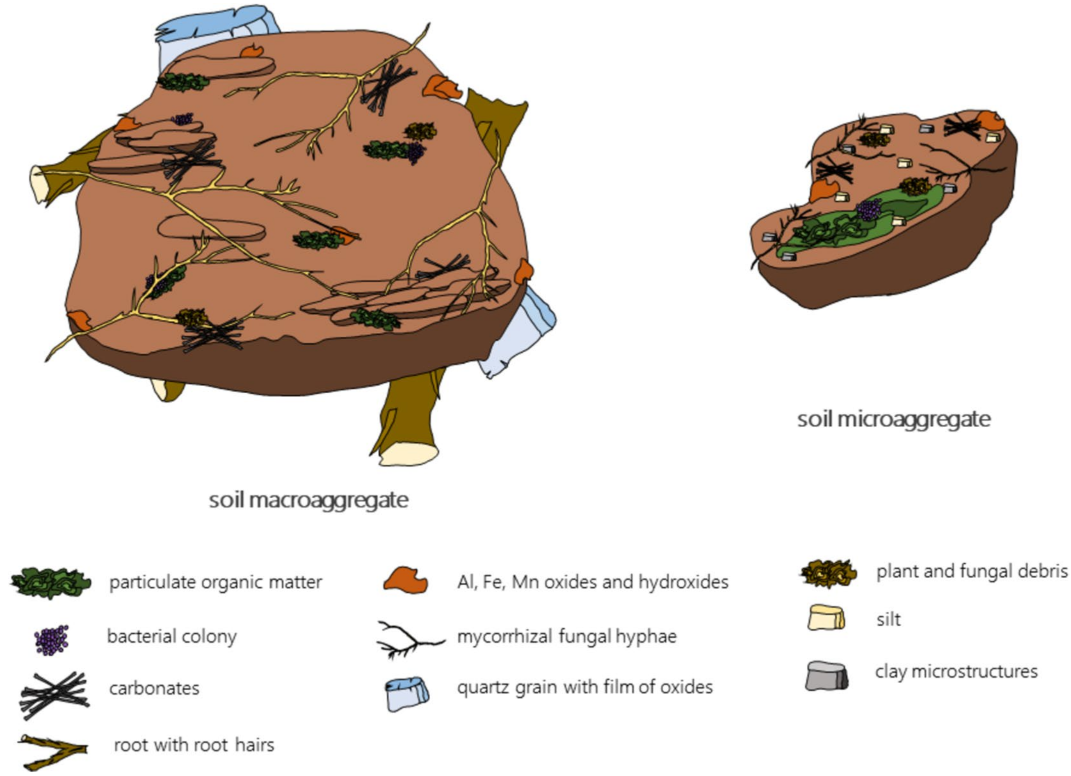

Fig. 5 Structure of soil macro- and microaggregates (prepared based on Yudina et al. (2018))

the field (first addition was on 2014, second on 2018). The first addition did not change soil porosity significantly. Ghorbani et al. (2022) obtained similar results. BC (rice straw-derived, obtained at 500℃) added at dose 10 t ha^{-1} significantly increased the proportion of micropores of sandy loam soil by 33% compared to the control, and 54% increase in mesopores content. For 5 t ha^{-1}, the mesopores amount increased by 38%. Both doses had little impact on macropores. Previously mentioned report of Sokołowska et al. (2020) showed that addition of sunflower husk BC at 5% dose to Dystric Cambisol resulted in increase in macropores content from two groups (of average size of 1.58 µm and 4.77 µm) to the average size of 5.78 µm.

Some studies reported the decrease in soil porosity after BC addition because pores were clogged by added particles (Murtaza et al. 2021). This reduction was not dependent on BC dose (Villagra-Mendoza and Horn 2018).

3 Zeolites

Zeolites are aluminosilicates with three-dimensional framework consisting of loosely bound cations as well as [AlO_4] and [SiO_4] tetrahedra linked by oxygen atoms. Their crystal structure is capable of hydrating and dehydrating while having no changes in the crystal lattice (Louhar et al. 2020; Jarosz et al. 2022). Zs general empirical formula is $M_{2/n}O\ Al_2O_3\ xSiO_2 \cdot yH_2O$, where M refers to alkali or alkaline earth element, n, to its charge. Zs are known as 'molecular sieves' (Khaleque et al. 2020; Louhar et al. 2020) because of their micropores with specific channels and voids (Cataldo et al. 2021; Louhar et al. 2020). Zs usually occur as volcanogenic sedimentary minerals in nature. However, they can also be produced in a laboratory. Synthetic Zs are typically characterized by superior sorptive abilities towards ions and molecules (Khaleque et al. 2020; Król et al. 2020), improved regenerability, and greater capacity to bind water (Jarosz et al. 2022; Rajabi and Ardakani et al. 2020).

Numerous researchers have employed organic waste for the Zs synthesiss (Jarosz et al. 2022; Khaleque et al. 2020; Król et al. 2020). Such utilizing waste holds great environmental importance. Among industrial wastes that are suitable for Z synthesis are those of substantial silica and alumina contents, i.e., blast furnace sludge, iron ore tailing, rice husk ash, coal fly ash (FA), lithium slag, paper sludge ash, and many others. So far, FA has been used in many studies (Jarosz et al. 2022; Khaleque et al. 2020). It constitutes a significant portion, ranging from 65 to 95%, of the waste produced during the coal combustion for energy production. Globally, the annual volume of generated FA exceeds 800 million metric tons. A certain amount of it can be transformed into Zs through a hydrothermal reaction. This production method is of high simplicity and low energy consumption. The FA conversion can also be accomplished through, molten-salt method, ultrasonic method, microwave method (Jarosz et al. 2022), fusion method, alkali activation, synthesis by dialysis (Król et al. 2020), as well as sol–gel method (Khaleque et al. 2020).

To add Z to the soil, the methods similar to those used for BC can be applied. Arrobas et al. (2022) plowed the ground to a depth of 25 cm, and then chiseled to level the surface. Then, Zs were manually spread on the field and mixed, making a final pass with a cultivator. Vrînceanu et al. (2019) manually scattered Zs over the surface and then mixed with the top layer of soil (depth 0–20 cm).

So far, it was stated that Z application improves water retention and porosity of the soil (Jarosz et al. 2022). Due to their slight alkaline nature, they stabilize soil pH level and thus minimize the need for lime (Cataldo et al. 2021). All these positive effects make quantity and quality of the obtained crops significantly better (Jarosz et al. 2022; Manjaiah et al. 2018).

3.1 Impact on water retention in soil

Zs offer a notable capacity to retain water, even 60% of their weight (Cataldo et al. 2021), which is especially advantageous during drought as well as in the regions where water availability is limited (Jarosz et al. 2022). Water located within Z pores can undergo evaporation or re-absorption without any threat to its crystalline structure (Cataldo et al. 2021).

Belviso et al. (2022) revealed that FA-derived Z enhanced water retention of silty loam soil and reduced its drainage ability, which was evidenced by the reduction in hydraulic conductivity at saturation occurring with increasing Z dose. The observed changes were dictated by alteration in PSD of the amended soils, which led to the reconfiguration of their internal system and favored the development of a clay-like soil structure. Essentially, adjusting the PSD shifted the range of available water toward higher soil moisture levels as the amount of Z added increased. What is more, the performed experiments indicated that treatments using higher concentrations of synthetic Z (5% and 10%) caused a substantial reduction in sunflower growth. Z concentrations ranging from 1 to 2% led to a moderate reduction in growth. The number of leaves decreased slightly at lower Z concentrations, but decreased by more than half when the Z concentration reached 10% (the control plants had about 14 leaves). A comparable reductions were observed for leaf area. In the end of the experiment, this parameter decreased from 456 cm^2 to 212 cm^2 after the treatment using 1 and 2%, to 67 cm^2, using 5%, and to 24 cm^2, using 10%. In this case, the Z addition made water unavailable to plants.

Ghorbani et al. (2022), mentioned in Sect. 1.1 and 1.2, in addition to the effect of BC, examined the effect of Z on soil hydrological properties. They added 5 and 10 t ha^{-1} of anzymite to the soil. This amendment had no significant impact on PWP. Also, Z had no significant effect on AWC at any dose. This was probably dictated by completely different soil and Z types applied in this study (compared to the previous one). K_s was increased by 174% for 5 t ha^{-1} dose and 303% for 10 t ha^{-1} dose. The authors observed that incorporating BC into a sandy loam soil was evidently more advantageous than adding Z due to its distinctive structural features. Indeed, owing to their coarse nature, particles of natural Z disrupted soil structure, scattered soil particles, elevated water loss, and consequently adversely affected plant development. On the other hand, the study of Khalifa et al. (2019) showed that the addition of Z at dose 9.52 Mg ha^{-1} increased FC, PWP, and AWC. For clay soil, they equaled 43.9%, 19.09% and 24.81%, respectively, while for sandy soil, 8.28%, 2.91% and 5.37%. Natural and synthetic Z effects on water retention of soil are summarized in Table 1. Some properties of synthetic Zs and their impact on soil condition are presented in Fig. 6.

3.2 Impact on soil structure

The impact of Zs obtained from waste on soil structure has not yet been described in detail in the literature. Previous reports described the effect of natural Zs as promising. The applied materials increased compression strength of the soil samples, increased overall soil porosity, but reduced BD (Jarosz et al. 2022; Mondal et al. 2021).

Ali et al. (2022) performed direct shear tests (DST) and unconfined compression strength tests (UCS) on soft soil samples containing varying proportions (0.2%, 0.4%, 0.6%, 0.8%, and 1%) of nano-zeolite ($Na_2Al_2Si_2O_8$, supplied by *Nano Research Lab*). They revealed that the introduced material enhanced shear strength of the soil specimens, but it was depending on duration of the curing period. For samples stabilized with 1% nano-zeolite, the unconfined compression strength was 10.2 and 16.7 times greater at 7th and 28th day of curing, respectively, compared to the untreated soil. Higher dose of nano-zeolite reduced deformability of the soil samples, which was a result of decreased failure axial strain. Table 2 presents the influence of natural and synthetic Zs on soil structure.

3.2.1 Bulk density

Aslam et al. (2021) added different rates of Zs (1, 3, and 5 t ha^{-1}) together with nitrogen (0 and 140 kg ha^{-1}) to the soil. A clear impacts of these treatments were noted only after 3 consecutive years. What is more, only the one with the highest Z rate (5 t ha^{-1}) yielded promising results. It notably changed several soil properties compared to the control, i.e., increased soil electrical conductivity (EC) by 24%, decreased BD by 2.5%, improved WHC by 20.6%, and made total carbon

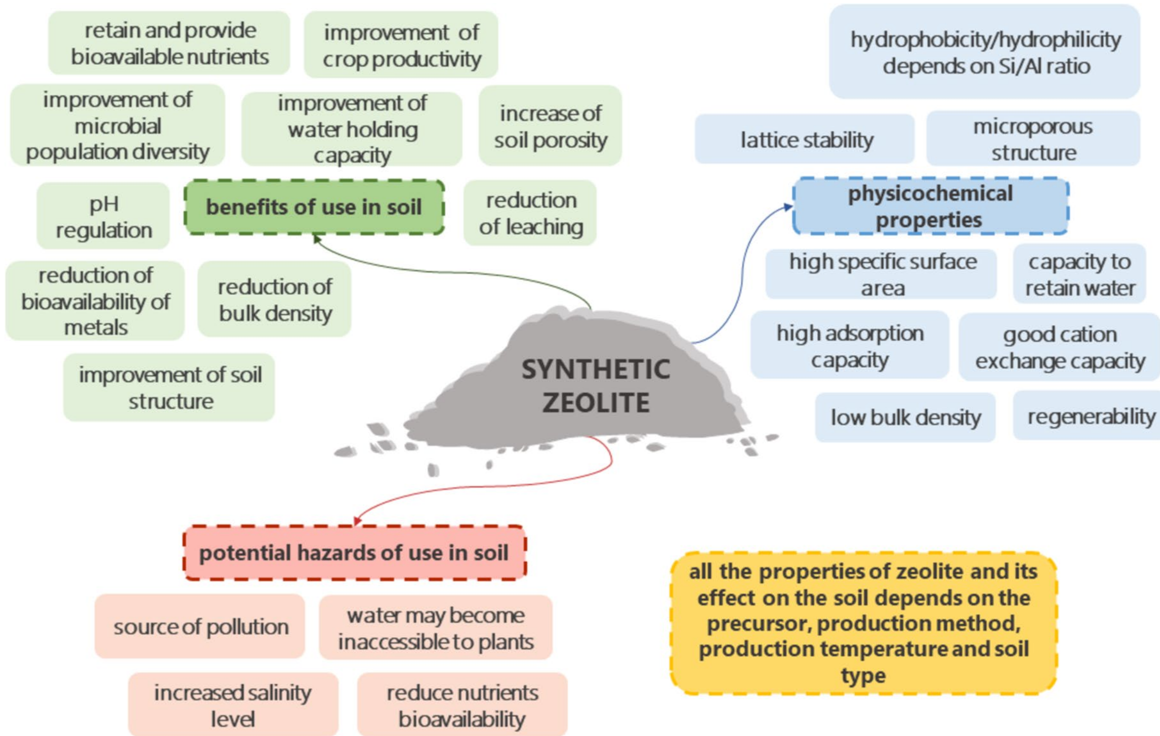

Fig. 6 Properties of synthetic zeolite and its impact on soil condition

content higher by 22%. The Zs amendment had no significant impact on the soil pH value throughout the 3-year experiment.

Khalifa et al. (2019) performed studies on clay and sandy soils with addition of 4.76 and 9.52 Mg ha^{-1} of Z. BD of both soils slightly decreased after amendment, which may be attributed to the decrease in total porosity. For 9.52 Mg ha^{-1}, it decreased from 1.22 to 1.19 g cm^{-3} in clay soil, and from 1.66 to 1.60 g cm^{-3}, in sandy soil. The results of Ghorbani et al. (2022) were similar. For sandy loam soil, the decrease in BD from 1.42 g cm^{-3} to 1.41 and 1.38 g cm^{-3} for 5 and 10 t ha^{-1} anzimite dose, respectively, was observed.

3.2.2 Aggregation

Amirahmadi et al. (2022) applied natural Z (anzimit) in 5, 10, 15 g kg^{-1} doses to Cd-contaminated soil. The 5 g kg^{-1} dose led to a substantial rise in both average weight diameter of aggregates, from 0.35 mm to 2.79 mm, and water stability of aggregates, from 51.6% to 80.7%. What is more, Cd bioavailability significantly decreased (by 86.84% for 5 g kg^{-1} dose), which resulted in better corn growth.

Ghorbani et al. (2022) measured MWD of sandy loam after the addition of 5 and 10 t ha^{-1} dose of anzimite. The treatment resulted in decrease in MWD from 0.68 mm (control) to 0.61 mm (5 t ha^{-1}), and 0.35 mm (10 t ha^{-1}). This was probably caused by the substitution of Ca^{2+} and Mg^{2+} on the soil clays by exchangeable Na^{+} provided by Z, what led to soil particle dispersion. This resulted in the disintegration of soil aggregation, as the flocculation of clay particles was a fundamental requirement for the formation of aggregates. The authors also explained this phenomenon in the context of the size of Z particles. Z size placed between 2.5 and 5 mm in size, so the smoothness and aggregation between the soil matrix particles declined. This hypothesis was supported by the fact, that there was a large amount of drainage water during irrigation (more than 70% of water discharged from the Z-containing pots (at dose 10 t ha^{-1}) comparing to the control).

Mirzaei Aminiyan et al. (2015) used mean weight diameter of water-stable (MWDw) aggregates as an index of aggregate stability and strength of Haplocalcids soil (loamy sand) amended with natural Z at 10% and 30% doses. The MWDw increased from 0.5 mm to 0.8 mm in the base of 10% dose, and to 1.00 mm, in the case of 30% dose of Z.

3.2.3 Porosity

Impact of Z on porosity depends on the system tested. For example, Mondal et al. (2021) observed that application of natural Zs in sandy soils lowered BD, which in turn altered soil water retention and air porosity. Nevertheless, the total soil porosity remained unaffected. Jarosz et al. (2022) concluded that Zs can increase porosity in clay soils. Khalifa et al. (2019) performed porosity studies on clayey and sandy soils. They reported that total porosity increased in both sandy and clay soil, due to application of Z at dose of 4.76 or 9.52 Mg ha^{-1}. It changed from 53.96% to 54.72% or 55.09% in clay soil, as well as from 37.36% to 40% or 41.51% in sandy one. Khalifa et al. (2019) performed studies on clay and sandy soils with addition of 4.76 and 9.52 Mg ha^{-1} of Z. The total porosity increased very slightly for both amendments, from 53.96% to 54.72% and 55.09%, in clay soils, and from 37.36 to 40% and 41.51% in sandy soil. The increase in porosity was probably due to the high porosity of Z, which additionally led to slight decrease in BD. Ghorbani et al. (2022) studied also pores proportion after anzimite amendment. Both doses (5 and 10 t ha^{-1}) did not significantly alter micro- and mesopores of sandy loam soil. However, the 10 t ha^{-1} dose significantly increased macropores content. There was 61% rise compared to the control.

4 Comparison of the impact of biochar and zeolite on soil condition

Comparing the impact of BCs and Zs on soil condition is problematic because the experiments described in the literature were conducted on different types of soils and the observed effects varied greatly. However, there are some similar and unique effects for these amendments.

4.1 The similar effects

The parameters that changed to a similar extent after applying BC and Z are BD, MWD, and total porosity (Tables 1, 2). Surprisingly, neither BC nor Z may have positive effects on the soil and yields. Arrobas et al. (2022) described such a situation. They did not note positive effects of BC (wood biomass of silver wattle, Ecochar®, 10 t ha^{-1}) and Z (clinoptilolite-based, 5 t ha^{-1}) on loamy soil.

4.2 The unique effects

The effects of adding BC to the soil undoubtedly include an increase in the organic matter content. If the Z is added to the soil, it remains practically unchanged due to the Z composition. Such effect was observed in Ghorbani et al. (2022). Organic matter content changed after BC addition to sandy loam soil from 0.87 to 1.31%, whereas after Z addition, to 0.91% (the dose of BC and Z was 5 t ha^{-1}). The use of BC also increase cation exchange capacity (CEC) of the soil. Ghorbani et al. (2022) observed a greater increase in CEC after adding BC to the soil than after Z amendment. These changes were from 24.5 cmol kg^{-1} to 115.1 cmol kg^{-1} and 38.5 cmol kg^{-1}, respectively, for 5 t ha^{-1} doses. Zheng et al. (2020) noted that CEC of the soil was increased by 35.3%, 11.8%, and 23.5% when BC (rice husk, produced at 400 °C), Z, and their combination were added successively at the dose of 5%.

5 Application Potential. What is the scenario that both Z and BC can be used simultaneously?

Literature reports describing the exact impact of the simultaneous addition of BC and Z on the physicochemical parameters of soils (water retention, structure, etc.) are very scarce. Harhash et al. (2022) demonstrated that Z and BC, applied together, had positive impact on plant growth and development. This was connected with improvement of soil condition. Because of porous nature, they improved water retention of soils, particularly in regions where water retention was scarce. BCs and Zs can also be helpful for the soils with coarse texture that are not well-suited for cultivation (Villagra-Mendoza and Horn 2018).

Liu et al. (2023) used clinoptilolite (natural Z) with apple tree branch BC. Carbon-rich material was applied to improve fertility of the selected soil, whereas Z was used to mitigate the adverse impact of BC on the geotechnical properties of vegetation concrete, i.e., an artificial substrate allowing ecological protection of damaged slopes. A great potential of simultaneous application of BC and Z was also described by Gondek et al. (2023). They used willow-derived BCs (produced at 350 and 550 ℃) and fly ash-derived Na-P1-type Z separately and together in a two-year pot experiment in artificially contaminated (with cadmium, lead and zinc) sandy loam soil. Then, the two grass species were sown (cocksfoot and tall fescue). When additives were added separately, the electrical conductivity of the soil did not change significantly. However, when the mixture of 550℃ BC and Z was added to the soil, EC increased the most significantly in the system with cocksfoot as well as with tall fescue (from 0.387 to 0.512 and from 0.353 to 0.525 mS cm^{-1}) in the first year of the experiment. In the second year, EC increased in all tested systems, however, the highest increase was observed for the pots, where the BC prepared at 350℃ was added.

Despite these reports, there is still a need to carry out field tests to determine the long-term impact of simultaneous addition of BC and Z on the soil properties. Hussien (2023) compared impact of BC (prepared from sugarcane bagasse at 300 °C, 5% dose), nano-zeolite (5%), and their combination (2.5% each) on lead toxicity, but also on sandy loam soil physical properties. Soil BD decreased the most when the mixture was used (from 1.49 g cm^{-3} to 1.42 g cm^{-3}). The changes in total porosity were similar for the BC application and the BC-Z combination (14% and 13% increase, respectively). Z applied alone contributed to 9% increase in total porosity, whereas BC and nano-zeolite clearly influenced AWC. They made it higher by 20 and 14%, respectively, and their mixture, by 21%. What is important, the combination of BC and nano-zeolite resulted in the highest decrease of the lead accumulation in roots (37%) (for BC, it was 31% and for Z, 28%). The metal accumulation in shoots decreased by 41%, 34%, and 40%, when BC, nanozeolite, and their combination were applied.

6 Economical benefits

Circular Economy Strategy of European Commission as well as "Closing the Loop" Action emphasize significant value of bio-based resources, including BC, and represent an innovative, research-driven approach aimed at optimizing their sustainable management and utilization (Nematian et al. 2021; Banu et al. 2020). BC is a material of growing importance from both ecological and economic perspectives. Its production can be relatively economical, especially when agricultural or forestry waste of high availability on a local scale is applied as a precursor. BC production can also be helpful in reducing costs of waste disposal. What is more, due to the fact that BC can limit soil erosion and groundwater pollution, its application can result in cost savings related to environmental protection.

According to Fortune Business Insights analysis called 'Biochar Market Size, Share & COVID-19 Impact Analysis, By Technology (Pyrolysis and Gasification), By Application (Farming, Livestock, Power Generation, and Others) and Regional Forecasts, 2023–2030', the BC market value in 2022 was $184.90 million and is expected to grow from $204.69 million in 2023 to $450.58 million in 2030. It exhibits a compound annual growth rate (CAGR) of 11.9% over the entire forecast period (Fortune Business Insights 2023a).

Profitability and desirability of the BC production and application are highly uncertain and vary significantly depending on specific factors such as location, feedstock type, production scale, pyrolysis conditions (e.g. temperature, pressure, gasifying agent, time), BC pricing, the crops being cultivated, and the potential integration of externalities. For further development and implementation of BC, these factors must be evaluated on a case-by-case basis (Campion et al. 2023). In general, higher temperatures increase syngas production, but decrease BC output. To optimize these production processes, integrated systems combining BC upgrading and syngas enhancement are recommended, along with an economic analysis (You et al. 2018). The price of BC significantly affects its attractiveness as a soil amendment. In general, lower yields in BC production, which are achieved through fast pyrolysis or higher temperatures, are usually more profitable. This is because the byproducts generated are usually more valuable than the BC itself, leading to higher overall revenues (Campion, et al. 2023). The maximum BC costs that farmers could incur were estimated taking into account the type of crop grown, the achieved yield increase and the duration of BC action (Sessions et al. 2019; Campion et al. 2023). Potatoes and alfalfa emerged as the most promising crops because of their high value per hectare. Yield increases of around 2% for potatoes and 7% for alfalfa would need to cover production costs, assuming these increases were sustained over five years. On the other hand, crops such as wheat, barley and hay would require yield increases exceeding 15%. Assuming a 10% yield increase over five years, wheat farmers could afford to pay up to $250/ha.

Campbell et al. (2018) assessed financial feasibility of co-production of biofuel and BC from forest biomass over 20-year project using net present value as a metric. They showed that in the case of simultaneous production of biofuel and BC, revenues were -24.2 million dollars at the average historical market price of biofuel. In the waste management scenario, total revenues were also negative and amounted to -USD 5.5 million. Sahoo et al. (2019) conducted a techno-economic evaluation of BC production (slow pyrolysis) from forest residues (woodchips) using a portable system. Moreover, with technological enhancements, the production costs of BC could potentially be reduced even by $470 per oven-dry metric ton. Kumar et al. (2020) in his economic analysis covering Kung et al. (2013) noticed that a fast and slow pyrolysis methods indicated the BCs value equal $2.85 and $10.98 per ton of feedstock, respectively. However, fast pyrolysis resulted in a net loss of $26.9 per ton of feedstock, while slow pyrolysis led to a net loss of $20.5 per ton of feedstock. This discrepancy can be attributed to the higher electricity generation and reduced economic and environmental benefits associated with fast pyrolysis. However, according to Harsono et al. (2013), slow pyrolysis could also be feasible when palm oil empty fruit bunches were used as a precursor. Annual expenses related to BC production at the plant amount to $523.6 for each ton of raw material. In contrast, the income generated from selling BC totals $531.6 per year. Snyder (2019) compared fast pyrolysis at 500 °C with slow pyrolysis at 400 °C. While both had a positive net present value, the net present value for fast pyrolysis was nearly three times higher, despite operating at the same scale. Bio-oil value was assumed at 500 USD/Mg, compared to 35 USD/Mg for BC. Lu and El Hanandeh (2019) focused solely on fast pyrolysis, but explored a range of temperatures from 300 °C to 600 °C in 50 °C increments. They found that 300 °C was the least desirable, while the highest profitability was achieved at 550 °C.

Microwave pyrolysis has recently attracted attention due to its potential advantages, such as reducing process time, minimizing the need for feedstock drying, allowing for rapid and convenient start-up and shut-down of the process, and producing BC of higher quality (Campion et al. 2023). Sessions et al. (2019) also compared thermal pyrolysis with microwave one. In all the scenarios evaluated, thermal pyrolysis had lower production costs, approximately 485 USD/Mg biochar, compared to 600 USD/Mg biochar for microwave pyrolysis. Latawiec et al. (2021) demonstrated comprehensive economic analysis of application of sunflower husk and woodchips BC (obtained by pyrolysis at 450–550 °C) in soybean (*Glycine max* L., the variety Elegance F1) cultivation in Calcaric/Dolomitic Leptosols (Ochric). They stated that applying BC at rates of 40, 60, and 80 t ha^{-1} did not yield a profit when compared to traditional soil amendments like NPK fertilization. For BC to become economically viable, the break-even prices should be 39.22$, 38.2$, and 23.53$ for 40, 60, and 80 t ha^{-1} doses, respectively. However, the cost of BC used in this experiment was 85.33$. The payback period for the 40 and 60 t ha^{-1} doses was estimated to be 3 years. With a subsidy of 30$ per ton of CO_2 for carbon sequestration, the use of BC may become profitable in the first year of soybean production. Patel and Panwar (2024) focused on the 0, 4, 8, 12, 16, 20, 24, and 28 t ha^{-1} BC doses. They concluded that the application of 8 t ha^{-1} is feasible due to the highest benefit–cost ratio (1.476). Aller et al. (2018) examined three different BC application rates (22, 45, and 90 Mg/ha) and assumed that the effects of a single application would last for 32 years. They found that the increased crop yield reached at higher application rates does not compensate for the higher purchase costs. What is more, Williams and Arnott (2010) assessed the BC application costs for different rates using broadcast-and-disk and trench-and-fill methods. The costs for broadcast-and-disk method varied from 71.66 to 741.32 USD ha^{-1} for an application rate of 6.18 and 123.55 Mg ha^{-1}, respectively. The application costs per 25 Mg of BC decreased from 11.60 to 6 USD Mg^{-1} (the cost of disking is independent of the application rate). In contrast, the trench-and-fill method showed more variation in costs, ranging from 64.25 to 3163 USD ha^{-1} for 12.36 and 185.33 Mg ha^{-1}, respectively. The cost of biochar application for this method increased from 5.20 to 17.10 USD Mg^{-1}, largely due to the method more labor-intensive nature. However, since 2010 new agronomic methods of BC application have been introduced, which could also impact the whole application costs.

Ezz et al. (2023) described how sustainability, bio-energy, economic viability, and waste reduction from rice straw (RS) aligned with the sustainable development goals (SDG). The RS raw material was utilized through simultaneous production of biogas and BC using a combined process involving hydrodynamic cavitation, anaerobic digestion, and pyrolysis. The performed production turned out to be profitable yielding 127.9 USD per ton.

According to Fortune Business Insights analysis 'Zeolite Market Size, Share & COVID-19 Impact Analysis, By Type (Natural [By Application {Construction & Building Materials, Animal Feed, Wastewater Treatment, Soil Remediation, and Others}], Synthetic [By Application {Detergents, Catalysts, and Adsorbents}]), and Regional Forecast, 2023–2030', the total value of the global zeolites market in 2022 was USD 6.14 billion. It is predicted to increase from USD 6.39 billion in 2023 to reach USD 8.55 billion by 2030, demonstrating a CAGR of 4.2% throughout the forecasted period (Fortune Business Insights 2023b). The demand for Zs is expected to increase significantly over the forecast period due to stringent regulations on the use of phosphates in detergents. Moreover, various applications of Zs are increasing the demand for them, which creates opportunities for the Zs market in the coming years (Fortune Business Insights 2023b).

Before starting the construction of a Zs production line, two important economic factors should be taken into account: the assessment of the expected demand for Zs that will be produced using the proposed technology and the financial assessment of the project itself (Szerement et al. 2021). Hong et al. (2017) conducted a cost–benefit analysis of coal fly ash conversion into Na-A Z via fusion method. The total capital expenditure of the project includes various elements, including but not limited to plumbing, civil works, measurement and control equipment, electrical works, general administrative costs, contingencies, design, engineering and procurement. They are set as part of total direct expenditure. Similarly, the annual operational expenditures comprise labor, maintenance, and supervision costs, in addition to expenses for raw materials, utilities, and wastewater treatment. Despite a relatively low Z selling price ($0.9286/kg), the production process demonstrated profitability, with a net present value of $126,338,000 and a profitability ratio of 1.23. Profitability ratio is the ratio of the present value of future expected cash flows to the initial amount invested in the project. Ziejewska et al. (2023) estimated production costs for Z Linde Type A, i.e., gismondine and sodalite. The unique aspect of this research involved the combustion of lignite in three circulating fluidized bed boilers for the purpose of transforming them into Zs. The production costs ranged from $3.82 to $6.36 per 1 kg, resulting in a potential price reduction of up to 99.5% for commercial Z.

7 Conclusions and future prospects

Studies on the impact of Zs on the soil environment are much less frequently performed than those using BCs. The research on Zs and various types of soil, including field experiments, is especially needed. In addition, some works on BC do not contain information on the type of feedstock or pyrolysis temperature, which does not allow to compare individual carbon-rich materials.

Based on the available data, it can be stated that both BCs and Zs have good sorptive properties, which usually contributes to better growth of crops. Comparing BCs and Zs and choosing which one is more promising depends on the specific purpose and type of soil to which they are to be applied. BC usage contributes mainly to providing organic matter and improving soil structure, while Zs are applied for enhancing water retention. However, it should be emphasized that the selected Z should not excessively bind water, providing plants with adequate access to it. Combinations of these materials may also be considered to provide benefits in both improved soil structure and water retention. The use of BC and Z simultaneously in remediation techniques should be the subject of research for the near future.

BC presents an economically attractive option because of its wide-ranging applications in agriculture, industry, and environmental protection. Nevertheless, the economic benefits of its utilization are contingent on accessibility of raw materials and applied production method. Regarding synthetic Zs, the price of their production may be lowered when properly selected method of production is used. An important aspect of BC and Z production is that they are made from waste materials, which meets the SDG assumptions. This could encourage policymakers as well as the public and private sectors to invest in projects to convert biomass or waste from the energy sector into soil additives.

Acknowledgements This review was financed by National Science Centre, Poland (2021/41/B/NZ9/03059).

Author Contributions Sylwia Kukowska: Conceptualization, Investigation, Writing – Original draft preparation, Katarzyna Szewczuk-Karpisz: Writing – Reviewing and editing, Supervision, Project administration.

Data availability Not applicable.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interest The authors have no relevant financial or non-financial interests to disclose.

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