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Enhancing agricultural productivity with biochar: Evaluating feedstock and quality standards

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ABSTRACT

The biochar standard could exert profound influences on the sustainable and sound production and application of biochar to address the agriculture and environment problems. Therefore, the feedstock and quality requirements of biochar were summarized and compared based on six standards of International Biochar Initiative (IBI) Biochar Standards in USA, European Biochar Certificate (EBC) in Europe, Biochar Quality Mandate (BQM) in UK, Code of Practice by Australia New Zealand Biochar Initiative (ANZBI) Inc., Biochar of agricultural industry standard in China (CNAIS) and Singapore Standard (SGS). The comparison mainly focuses on the feedstock of biochar, properties requirements, proposed limits for heavy metals and organic pollutants, and packaging requirements set by biochar standards. Based on the published studies, the basic properties, heavy metals and polycyclic aromatic hydrocarbons of biochar are summarized and compared with biochar standards. The proposed recommendations on biochar for soil application will help to further promote the long-term and sustainable benefits of biochar management.

1. Introduction

Biochar has received much attention for its potential to enhance soil properties, consequently upgrade crop quality, sequester carbon, and mitigate climate change when applied to soil, and thus has been widely applied to address the agriculture and environment problems (He et al., 2021; Lehmann et al., 2006; Sun et al., 2021b). The production of biochar and its application in agriculture have been increasingly developed by biochar users and producers worldwide (Iwuozor et al., 2023; Wang et al., 2020; Wu et al., 2019). Biochar from agro-wastes can not only be used as soil amendment and remediation, but can also be customized as activated carbon substitute and nanomaterials, which would play a critical role in agriculture and environment for green sustainable development (Bao et al., 2024; Basta et al., 2022; Ho et al., 2021). However, the properties and quality of biochar are highly affected by the selected feedstock and the production process, which can vary widely, and then affect the application effect of biochar (Chen et al., 2019; Dixit and Ahammed, 2023). Therefore, biochar standards are of great importance to ensure its quality and safety for its sustainable and ecological production and application.

The internationally adopted voluntary biochar standards have been established in Europe (European Biochar Certificate, EBC), in the UK (Biochar Quality Mandate, BQM) as well as in the USA (International Biochar Initiative, IBI), to narrow the regulatory gap for biochar production and application. The national biochar standards developed in different latitudes by Australia and New Zealand, China and Singapore provide a code of practice for the sound production and agriculture application of biochar (ANZBI, 2020; CNAIS, 2022; SGS, 2023). The feedstock and quality requirements for biochar vary between these six standards. Therefore, a comparison of the differentiation of the six standards is of great benefit for the regulation of biochar production and application. Moreover, it is a global challenge to combat climate change by promoting the use of biochar, and fully understanding the similarities and differences among the standards will not only help to upgrade biochar quality, but also facilitate global cooperation and even the joint establishment of an international standard system.

This publication aims to illustrate and compare the feedstock and quality requirements of biochar for agriculture application by summarizing voluntary and national biochar standards including IBI, EBC, BQM, Australia New Zealand Biochar Initiative (ANZBI) Inc., Biochar of

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agricultural industry standard in China (CNAIS) and Singapore Standard (SGS). The comparison mainly includes the feedstock of biochar, properties requirements, proposed thresholds for heavy metals and organic pollutants as well as packaging requirements of the six standards. The recommendations of biochar for agriculture application such as feedstock, quality and packaging requirements, and the future prospects for the biochar industry are proposed for sustainable and sound production as well as environmentally friendly and economical application of biochar.

2. Biochar standards

The voluntary standard, European Biochar Certificate was published by the European Biochar Foundation in 2012 to guarantee the production and quality of biochar (EBC, 2012). The 9 primary contents are definition of biochar, biomass feedstock, requirements for keeping production records, biochar sampling, biochar properties, pyrolysis, sale and application, quality assurance and certification, as well as analytical methods. Two different biochar grades, including “basic” and “premium”, have been distinguished, mainly based on the threshold values for heavy metals and polycyclic aromatic hydrocarbons.

Version 1.1 of The Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil (IBI Biochar Standards) was published in 2013 (IBI, 2013). The standards have been updated in October 2014 with version 2.0 and in November 2015 with version 2.1 (IBI, 2014, 2015). The main contents of version 2.1 are biomass feedstock material and biochar production, biochar material test categories and characteristics, as well as general protocols and restrictions.

Biochar Quality Mandate (version 1.0) published in 2014 focused exclusively on biochar use as an addition to soil (BQM, 2013). The 7 regulatory requirements on biochar definition and feedstock, sustainability of biomass feedstocks, waste controls, producing technology and sampling methodologies, quality properties and toxicants limits, application of biochar in soils, as well as quality assurance and certification are specified. The differences between standard grade and high grade of biochar by BQM are the threshold values of heavy metals.

Based on IBI and EBC, the Code of Practice for the Sustainable Production and Use of Biochar by Australia New Zealand Biochar Initiative Inc. in 2020 set out industry practice for manufacturers and users in Australia and New Zealand due to the importance of biochar quality and properties (ANZBI, 2020). This Code of Practice specifies the definitions, feedstock requirements, pyrolysis production and its records, use with biochar grades and sampling and testing, handling and packaging, quality assurance and verification via certification. Biochar is categorized into three grades, “Biochar Premium Grade (BPG)”, “Biochar Standard Grade (BSG)” as well as “Biochar Industrial Grade (BIG)” on the basis of maximum concentration of impurities for agriculture use, animal feed as well as some industrial uses, while each grade of biochar would possess different carbon contents. The aim of ANZBI is to provide guidance on the sustainable production and safe utilization of biochar products.

The agricultural industry standard in China, Biochar, which was implemented in 2022, reported that biochar was classified into grade I and grade II in accordance with the carbonization and pollutants contents when applied to agriculture (CNAIS, 2022). Grade I biochar could be utilized directly in the soil and as a raw material of fertilizer products while grade II biochar must meet other requirements including risk control standard for soil contamination of agricultural land and standard of fertilizer product. This standard specifies the terms and definitions, requirements of appearance quality and technology attributes, sampling methods, test methods of sample preparation and attributes, inspection rules, as well as labeling, packaging, transportation and storage of biochar. Biochar standard could provide the requirements and guidelines of biochar for agriculture application.

Based on IBI, ANZBI and EBC, the Singapore Standard (SGS), Code of practice for the production and application of biochar (SGS, 2023), was developed in 2023 to standardly assess biochar quality in order to furnish biochar users with informed purchasing and utilization guidelines. The standard primarily specifies the suggested production conditions of biochar, the compulsory and voluntary attributes, as well as maximum concentrations of contaminants in biochar not only for agriculture application, but also for applications in horticulture, anaerobic digestion, construction materials, and activated carbon. The successful application of biochar in Singapore on the basis of SGS would facilitate the sound development of the biochar industry, paving the way for global sustainability through the export of biochar.

3. Feedstock of biochar

The feedstock utilized to manufacture biochar can significantly affect the quality and properties of biochar (Ippolito et al., 2020; Lataf et al., 2022; Otoni et al., 2024). For instance, the ash content, pH, and nutrient content of biochar can vary depending on the feedstock used. Therefore, it is important to select an appropriate feedstock for the intended application of biochar to soil. The feedstock of biochar required by 6 standards with different material origins and limitations are summarized in Table 1.

Based on the IBI standard, the definition of feedstock for biochar consisting of biological material and diluents is also given in the ANZBI standard. The six general biomass feedstock requirements are recommended, particularly the long transportation of the feedstock required with carbon assessment. The unprocessed feedstock, such as woody biomass or grass biomass, must have sustainable source and should not be contaminated, while the processed feedstock, which includes poultry litter, biosolids or processed wood, must be measured for acceptable levels of impurities (Table S1).

It is emphasised that the CNAIS will only apply to the biochar produced from agricultural and forestry botanical waste biomass. There are no feedstock restrictions due to the simple and specific feedstock source. The aim of strictly limiting biochar feedstock is to pave the way for the continued expansion or enrichment of non-plant source biochar standards in the future. For example, livestock manure biochar or sludge biochar can be separately formulated as a separate agricultural industry standard for the intended application.

The organic materials, including horticultural waste, food waste, sewage sludge and animal manure, used as feedstock of biochar are applied to the SGS with five detailed requirements regarding the removal of reactive impurities and treated or coated materials, declaration of feedstock material on the packaging and complete records of feedstock. It should be noted that feedstock should stem from untreated, unprocessed and uncontaminated organic materials with homogenization, sustainable harvest and localization.

Only organic wastes with a detailed positive list are used as permitted feedstock of biochar production in EBC. There are 6 other feedstock requirements relating to removal of non-organic waste, exclusion of paint, solvents and other organic or non-organic contaminants, sustainable manner of primary agricultural products, sustainable management of wood from forests or short rotation forestry plantations, transport distance, and complete records of feedstock.

Although there is no specified feedstock required by the IBI standard only relating to the biochar material, some requirements are applied to feedstock contents and quality. The processed feedstock grown on contaminated soils must meet the toxicant assessment tests repeated annually, while the toxicant assessment of unprocessed feedstock may be tested every three years. Municipal solid waste containing hazardous materials may not be considered as eligible feedstock, and the producers must ensure that biochar feedstock do not have hazardous materials.

There are ten feedstock requirements in BQM, firstly emphasizing that only biomass feedstock from agriculture, forestry, the related industries including fisheries and aquaculture, and the biodegradable fraction of industrial and municipal waste are considered for producing

Table 1
Feedstock of biochar standards.

	Feedstock	Feedstock limitations	Production technologies	Process temperature	Application
ANZBI- Premium	Biological material containing diluents	9 requirements^1	Pyrolysis	–	Agriculture use including animal feed
ANZBI- Standard					Most agriculture use excluding animal feed
CNAIS- Grade I	Agricultural and forestry botanical waste biomass	–	Pyrolysis	Min: 400 °C Max: 700 °C	Agriculture
CNAIS- Grade II					
SGS	Organic materials	5 requirements^1	Pyrolysis, Gasification	Min: 350 °C Max: 800 °C	Agriculture, other 4 applications^2
EBC- Premium	Only organic wastes	7 requirements^1	Pyrolysis (gasification)	Min: 350 °C Max: 1000 °C	–
EBC- Basic					
IBI	No specific feedstocks	Detailed requirements^1	Not specified	–	A soil amendment
BQM- High	Only biomass feedstocks	10 requirements^1	Not specified	–	Only an addition to soil
BQM- Standard					

Notes:
1: The detailed requirements are given in Table S2.
2: Other 4 applications- horticulture, anaerobic digestion, construction materials, activated carbon.

biochar. Compare with CNAIS, the biomass feedstock by BQM might be relatively complex and diverse, such as the agriculture biomass including vegetal and animal substances. The imported feedstock are required to meet full sustainability reporting requirements.

The pyrolysis and gasification are the dominant production methods of biochar while thermochemical conversion without specified requirements is stated by IBI and BQM. The minimum and maximum process temperatures are specified by CNAIS, SGS and EBC. Based on EBC, the end products from the carbonization processes including torrefaction, hydrothermal carbonization and coke production cannot be biochar.

The SGS provides guidelines for biochar applications in agriculture, horticulture, anaerobic digestion, construction materials and activated carbon, with the main differences being the different threshold values of heavy metal. The main aim of EBC is to guarantee sustainable biochar production and quality and thus there is no limit to the biochar application. However, the biochar definition indicated that biochar could be utilized for any purpose and might ultimately become the soil amendment.

4. Quality requirements of biochar

The compulsory tests in the ANZBI are organic carbon content, total carbon, $H:C_{org}$, ash content, pH, moisture content, density and impurities of heavy metal and organic pollutants, and the threshold values of three basic properties are given. Although there are no specific limits on ash content, pH, moisture content and density, the compulsory tests of these properties should be carried out and declared for certification. The SGS asks for the same compulsory tests on nine heavy metals and three organic pollutants with the ANZBI standard. The threshold values of organic carbon, ash content and $H:C_{org}$ are required to meet the recommended limits by SGS while there are no specific limits for pH, moisture content and density which should be declared. The threshold values of five basic properties regarding total carbon, fixed carbon, H/C, O/C, moisture content, nine heavy metals and two organic pollutants are specified by CNAIS.

Three categories of tests for biochar materials identified by the IBI are basic utility properties, toxicant assessment, as well as advanced analysis and soil enhancement properties. The basic utility properties and toxicant assessment are required to be tested for all biochars. The basic utility properties cover organic carbon, $H:C_{org}$, total nitrogen, total ash, pH, moisture, electrical conductivity, liming (if pH is above 7) and particle size distribution while toxicant assessment involves germination inhibition assay, heavy metal and organic pollutants. Organic carbon and $H:C_{org}$ must meet the threshold values of IBI, while the other basic utility properties should be declared without specific limits. The threshold values of two basic properties, eleven heavy metals and four organic pollutants are specified by IBI.

The threshold values of four basic properties with regard to total carbon, organic carbon content, H/C_{org}, O/C_{org}, seven heavy metals and three organic pollutants are specified by EBC, while volatile organic compounds, nutrient contents relating to nitrogen, phosphorus, potassium, magnesium and calcium, pH value, bulk density, water content, ash content and specific surface area must be available and listed and there are no requirements for specific limit values.

The necessary basic properties required by BQM are total carbon, organic carbon, hydrogen, heavy metal content, organic pollutants, pH, moisture content and long-term carbon stability. However, there are no specific limit values for total carbon, hydrogen, pH, moisture content and long-term carbon stability, however, all of which must be declared. The threshold values for two basic properties, eleven heavy metals and three organic pollutants are specified by BQM.

4.1. Basic properties for biochar

The necessary testing of carbon content is required by the IBI, BQM and SGS while there is no requirement for a specific value (Table 2). The required values of total carbon are different for the different grades of CNAIS, while the different grades of EBC and ANZBI have the same threshold value for carbon content (50 %). The EBC emphasizes that the carbon content of biochar must be higher than 50 %, and the produced char with carbon content lower than 50 % would not be categorized as biochar but as Pyrogenic Carbonaceous Material (PCM), which belongs to a completely different product category due to its high ash content. The total carbon and fixed carbon contents are both required by CNAIS with the threshold values of 60 % and 50 % for grade I as well as 30 % and 25 % for grade II respectively. The fixed carbon from 0 % to 90 % could be measured by thermogravimetric analyzer, proximate analysis or furnace (Adekanye et al., 2022; Adhikari et al., 2024; Enders et al., 2012; Yang et al., 2020). It would be simple and low-cost for manufacturing enterprise to obtain the multiple determination contents of fixed carbon by furnace, and thus the total carbon and carbonization degree could be predicted to facilitate the routine quality control of biochar.

Apart from EBC and CNAIS, the threshold values of organic carbon among four diverse standards are different depending on the selected feedstock and production conditions, but biochar shall have an organic carbon content of at least 10 % required by IBI and BQM. It is reported

Table 2
Basic properties of biochar standards.

	Unit	Total carbon	Organic carbon	Fixed carbon	H/C	O/C	Total ash	Moisture content
		%	%	%			%	%
ANZBI	Premium	>50	>30	–	≤0.7[1]	–	Not specified	Not specified
	Standard	>50	>30	–	≤0.7[1]	–	Not specified	Not specified
CNAIS	Grade I	≥60	–	≥50	≤0.4	≤0.2	–	≤30
	Grade II	≥30	–	≥25	≤0.75	≤0.4	–	≤30
SGS		–	P: 30–95, G: 70–95	–	≤0.7[1]	–	P: 5–70, G: <30	Not specified
EBC	Premium	≥50	–	–	<0.7[1]	<0.4[2]	Not specified	Not specified
	Basic	≥50	–	–	<0.7[1]	<0.4[2]	Not specified	Not specified
IBI		–	≥10	–	≤0.7[1]	–	Not specified	Not specified
BQM	High	Not specified	≥10	–	≤0.7[1]	–	Optional	Not specified
	Standard	Not specified	≥10	–	≤0.7[1]	–	Optional	Not specified

P: Pyrolysis.
G: Gasification.
Not specified: The specific limits are not required, but the measured values must be declared.
Optional: The properties are not required while the tests are conducive to guarantee biochar quality for enhancing soil.
Notes:
1. Molar ratio of hydrogen to organic carbon.
2. Molar ratio of oxygen to organic carbon.

that organic carbon contents of biochar required by IBI without requirement on total carbon could be classified into the following three classes, ≥60 %, ≥ 30 % and < 60 %, ≥ 10 % and < 30 %. The organic carbon content of biochar required by ANZBI is >30 %, which is higher than the threshold value of IBI and BQM. Although there is no specific classification and requirement for total carbon by SGS, the minimum values of organic carbon are 30 % and 70 % depending on the production conditions including pyrolysis and gasification while the maximum values are both 95 %. There is no requirement for organic carbon by CNAIS, mainly due to the potential error caused by their subtraction calculation between total carbon and inorganic carbon.

Biochar stability is primarily indicated by H:Corg, lower values of which are associated with greater stability. Apart from CNAIS, the other reviewed standards reported that biochar should have a H:Corg of less than or equal to 0.7. The grade I of CNAIS asks for a lower H:C of 0.4 than grade II (0.75), indicating a high requirement on direct application of biochar in agriculture. There are two vital factors considered for the total carbon selected to calculate H/C in CNAIS. Firstly, the total carbon measured by the elemental analyzer is adopted to lessen the calculation error of organic carbon. Secondly, the inorganic carbon rooting from biomass could also play a key role in carbon storage. Compared with the strict requirements of grade I, which is proposed to be conducive to the sustainable production of high-quality biochar by CNAIS, the reasonable threshold of grade II may encourage the stable development of small-scale enterprises.

The other indicator for biochar stability is the O/Corg ratio with the maximum of 0.4 required by EBC. Compared with grade II of CNAIS, there is also a high requirement on the O/C ratio in the grade I with the maximum of 0.2. Although O/C of grade II asks for the same value as that of EBC, the lower threshold of O/C might facilitate the large-scale application of biochar. It is suggested that the combination of volatile matter below 80 % and O:Corg below 0.2 or H:Corg below 0.4 might turn out the high carbon sequestration potential (Enders et al., 2012).

The threshold values of ash content and particle size are required by SGS. The particle size of biochar produced by pyrolysis and gasification has the same threshold value of 0.1–8 mm, while the threshold values of ash content are different. The maximum ash content of biochar produced by gasification is 30 % while biochar produced by pyrolysis could have an the ash content of 5–70 %.

Moisture content is one of the necessary or compulsory properties among these six standards, and CNAIS asks for the maximum of 30 %, while the other standards emphasise the declaration of biochar moisture content. The different biochar grades in the ANZBI, EBC and BQM would have the uniform basic properties, which differ from those in CNAIS.

The long-term effects of biochar on soil have been investigated through field experiment, and the basic properties for biochar are measured. The positive effects of wood biochar on soil properties and crop yields were found by 4-year field experiment with 4 m × 5 m plots, which demonstrated that biochar could facilitate the soil management of agroecosystem in humid tropical regions with long-term annual rainfall (Major et al., 2010). The biochar properties including pH (9.2), total C (72.9 %), total N, C/N, H/C (0.018), O/C (0.26 %), ash (4.6 %), Ca, Mg, P, K, Sr and CEC were reported. Biochar produced from maize stover could impose a better impact on soil aggregation of brown earth after a six-year field experiment with the plot size of 3.6 m × 10 m by elevating the soil organic carbon, microbial biomass carbon and easily extracted glomalin-related soil proteins (Sun et al., 2021a). The biochar properties such as pH (9.2), total C (66 %), total N, total P, total K and ash (15.57 %) were measured. The pH and ash are both measured, and the total carbon contents of biochar in the published studies are higher than 60 %, which meet the requirements of all standards. Additionally, H/C of wood biochar meet all of the biochar standards while O/C is higher than that required by grade I of CNAIS.

4.2. Heavy metal standards of biochar

The threshold values of heavy metal are shown in Table 3 while the minimum and maximum threshold values of ten heavy metals are shown in Fig. 1. The threshold values of molybdenum are required by IBI and BQM, while those of selenium are not declared by EBC and CNAIS. There are seven heavy metals required by all reported six standards (Fig. 2). It is speculated that there are three heavy metals that are only required by one of the six biochar standards, and the maximum limits of thalium required by CNAIS, cobalt declared by IBI and manganese suggested for high grade quality biochar of IBI are 2.5 mg/kg, 100 mg/kg and 3500 mg/kg, respectively (Table 3).

The minimum and maximum threshold values of heavy metal shown in Fig. 1 are obtained by comparing the threshold value of six standards based on Table 3. The threshold values of mercury are the smallest, followed by cadmium, while these of zinc are the largest, followed by copper. The threshold values of molybdenum have been required by IBI and BQM, and the maximum limit of molybdenum is declared by IBI and BQM-Standard while BQM- High has the smallest limit of molybdenum. Apart from CNAIS and EBC, the other standards ask for the threshold values of selenium. The minimum and maximum threshold values of selenium are required by SGS and IBI, respectively. Except for EBC, the threshold values of arsenic are required by five standards. The maximum limit of molybdenum is declared by IBI and BQM-Standard while ANZBI-

Table 3
Threshold values of heavy metal of biochar standards (unit: mg/kg).

		As	Cd	Cr	Co	Cu	Pb	Hg	Mn	Mo	Ni	Se	Ti	Zn
ANZBI	Premium	<2	<1	<80	–	<100	<10	<0.1	–	–	<30	<10	–	<200
	Standard	<15	<1	<100	–	<1000	<20	<0.2	–	–	<100	<50	–	<2000
	Industrial	<100	<20	<100	–	<6000	<300	<10	–	–	<400	<200	–	<7400
CNAIS	Grade I	≤13	≤0.3	≤90	–	≤50	≤50	≤0.5	–	–	≤50	–	≤2.5	≤200
	Grade II	≤15	≤3	≤150	–	≤200	≤50	≤2	–	–	≤190	–	≤2.5	≤300
SGS		<2	<1	<70	–	<100	<10	<0.1	–	–	<20	<1	–	<200
EBC	Premium	–	<1	<80	–	<100	<120	<1	–	–	<30	–	–	<400
	Basic	–	<1.5	<90	–	<100	<150	<1	–	–	<50	–	–	<400
IBI		≤100	≤39	≤1200	≤100	≤6000	≤300	≤17	–	≤75	≤420	≤200	–	≤7400
BQM	High	≤10	≤3	≤15	–	≤40	≤60	≤1	≤3500	≤10	≤10	≤5	–	≤150
	Standard	≤100	≤39	≤100	–	≤1500	≤500	≤17	–	≤75	≤600	≤100	–	≤2800

Abbreviations in the table:

As- Arsenic
Cd- Cadmium
Cr- Chromium
Co- Cobalt
Cu- Copper
Pb- Lead
Hg- Mercury
Mn- Manganese
Mo- Molybdenum
Ni- Nickel
Se- Selenium
TI- Thalium
Zn- Zinc

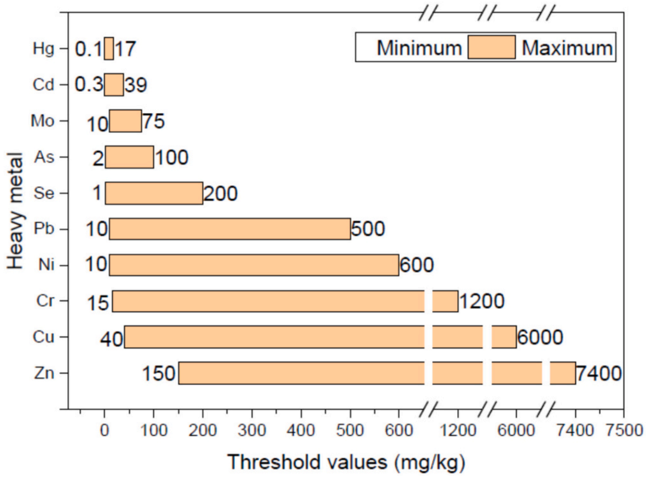

Fig. 1. The minimum and maximum threshold values of heavy metal.

Premium and SGS have the lowest limit of arsenic.

As shown in Fig. 2, the maximum limit of mercury and cadmium declared by IBI and BQM-Standard is significantly higher than those of other standards. The threshold values of mercury and cadmium declared by other standards are 0.3–3 mg/kg and 0.1–2 mg/kg, respectively. The SGS and ANZBI-Premium have the lowest limit of mercury and the CNAIS-Grade I has the lowest limit of cadmium.

The maximum limits of arsenic and lead declared by IBI and BQM-Standard are significantly higher than those of other standards. The threshold values of arsenic declared by other standards are 2–15 mg/kg, those of lead declared by other standards are 10–60 mg/kg except for the EBC standards with comparatively high lead of 120 and 150 mg/kg. The limit of arsenic and lead declared by SGS and ANZBI-Premium is the lowest.

The limit of nickel declared by BQM-Standard is the highest, followed by the IBI, CNAIS-Grade II and ANZBI-Standard. The limit of chromium declared by IBI is the highest, followed by CNAIS-grade II, BQM-Standard and ANZBI-Standard. The threshold values of nickel and chromium declared by other standards are 10–50 mg/kg and 15–90 mg/kg, respectively. The limits of nickel and chromium declared by BQM-High are the lowest, followed by SGS.

The maximum limits of copper and zinc declared by IBI, BQM-Standard and ANZBI-Standard are significantly greater than other standards. The threshold values of copper and zinc declared by other standards are 40–200 mg/kg and 150–400 mg/kg, respectively. The limits of copper and zinc declared by BQM-High are the lowest, followed by CNAIS-Grade I.

It is reported that biochar could be utilized as remediation agent and adsorbent to alleviate the heavy metals pollution in soil and water by affecting their mobility and bioavailability (Gong et al., 2022; Liu et al., 2023; Qiu et al., 2021). The wheat straw biochar produced at 500 °C exerts better remediation effects on Cd of neutral and saline-alkali soils than acidic soil (Zuo et al., 2023). The papermill sludge biochar manufactured at 600 °C had higher adsorption capacities for Ni, Cu and Pb in an aqueous solution, while rice straw biochar had higher adsorption capacity for Cd (Islam et al., 2021). The Cu contents of papermill sludge biochar and rice straw biochar are both low and meet the threshold values of six standards while the other heavy metals are not detected and the heavy metals of wheat straw biochar are not measured. Currently, the heavy metals of biochar are not rarely investigated perhaps due to the low levels. Wang and colleagues (Wang et al., 2023) found that the heavy metal (Pb, Ni, Cr, Cu and Zn) contents of biochar produced from horticultural waste met the threshold values of the IBI, ANZBI, CNAIS and SGS, while As, Se and Cd were not detected.

4.3. *Organic pollutants*

Biochar produced at higher temperature might contain organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). These persistent pollutants could be harmful to human health and the environment. Therefore, it is greatly essential to minimize the presence of potential organic pollutants in biochar. The threshold values of organic pollutants among biochar standards are shown in Table 4. These six standards have required the threshold values of PAHs, while PCBs, PCDDs and PCDFs are described by five standards other than the CNAIS standard. Except for PCDDs and PCDFs, IBI has set guidelines for the maximum concentrations of organic pollutants in biochar, and the threshold values of organic pollutants required by the other standards are significantly lower than those set by IBI.

equiv.: equivalency
Abbreviations in the table:
PAHs- Polycyclic Aromatic Hydrocarbons
B(*a*)P- Benzo (a) Pyrene
PCBs- Polychlorinated Biphenyls
PCDDs/Fs-Dioxins/Furans.

There is no difference in the limits for organic pollutants between the two grades of the BQM and CNAIS. There is a high requirement for the PAHs with the maximum of 4 mg/kg for premium grade of EBC, while

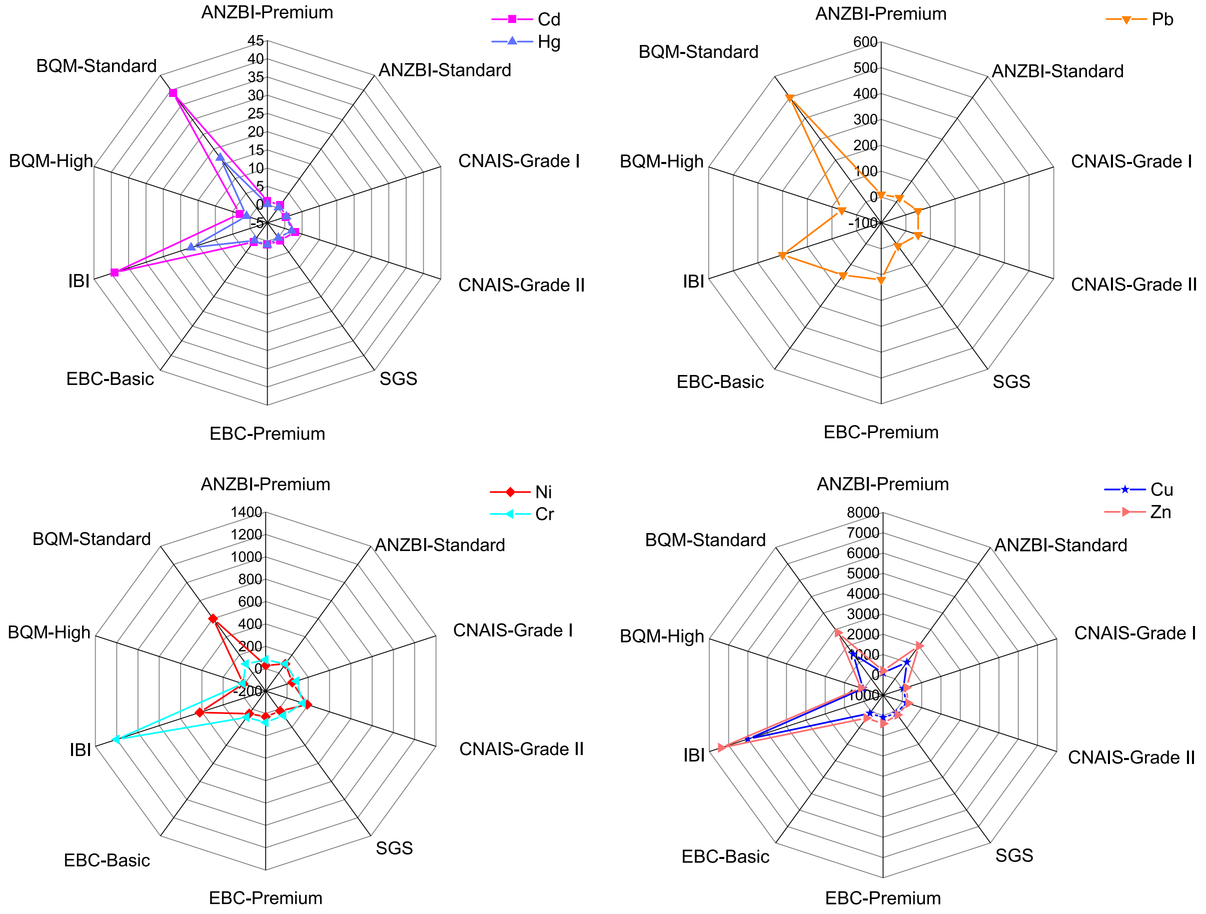

Fig. 2. Threshold values of heavy metal of biochar standards (the specified values are given in Table S3).

Table 4
Threshold values of organic pollutants of biochar standards.

		PAHs content	B(*a*)P toxic equiv.	PCBs	PCDDs/Fs toxic equiv.
	Unit	mg/kg	mg/kg	mg/kg	ng/kg
ANZBI	Premium	<4	–	Table S4	Table S4
	Standard	<6	–	0.2–1	<17
	Industrial	<300	–	0.2–1	<17
CNAIS	Grade I	≤6	≤0.55	–	–
	Grade II	≤6	≤0.55	–	–
SGS		<4	–	<0.2	<17
EBC	Premium	<4	–	<0.2	<20
	Basic	<12	–	<0.2	<20
IBI		≤300	≤3	≤1	≤17
BQM	High	<20	–	<0.5	<20
	Standard	<20	–	<0.5	<20

the PAHs content of basic grade could be below 12 mg/kg. The trigger value of PCBs is 0.35 ng/kg at 88 % dry matter for premium grade of ANZBI, while that of PCDD/PCDF is 0.50 ng/kg with the maximum of 0.75 ng/kg.

It is investigated the PAHs concentrations of biochar formed from softwood pellets at the highest pyrolysis temperature of 550 °C, and found that the water-soluble PAHs concentrations ranged from 1.5 to 2 μg/g, below the threshold values required by 6 biochar standards (Buss et al., 2015). However, the 16 US EPA PAHs concentrations of uncontaminated biochar measured by 36 h toluene extractions were 6.09 μg/g while the total concentrations of a gas-contaminated biochar and a liquid-contaminated biochar were 53.42 μg/g and 27.89 μg/g, exceeding the threshold values required by the biochar standard of ANZBI, CNAIS and SGS. The softwood pellets with additives might have unfavorable impacts on the PAHs concentrations and other properties of biochar.

It is reported that the total PAH concentrations of over 50 biochars varied from 0.07 μg/g (switchgrass 800 °C and pine wood 900 °C) to 3.27 μg/g (Kenya corn stover) depending on the biomass source. The highest PAH concentrations of biochars are generally found at the pyrolysis temperature of 350–550 °C while the higher pyrolysis temperatures (800–900 °C) contributed to the lower PAH concentrations (Hale et al., 2012). The PAH concentrations of biochars produced from cellulose fibres and cereal husk (600 °C), untreated wood (600 °C) as well as untreated wood and wood waste (600 °C) certified by the EBC were 0.55 g/kg, 0.93 g/kg, 0.25 g/kg by Py-GC/MS, while those of biochar leachate were 10.6 mg/kg, 17.6 mg/kg, 14.9 mg/kg (Ruzickova et al., 2021). Hence, the amount and type of PAHs are largely influenced by the feedstock and the pyrolysis conditions.

The PAH concentrations in soil amended with biochar for 3 years were 1.95 mg/kg in the field trial with plots (6 m × 3 m), higher than those in unamended soils (1.13 mg/kg) (Quilliam et al., 2013). The PAHs concentrations of rice husk biochar and wood biochar were 64.65 mg/kg and 9.56 mg/kg exceeding the threshold values of ANZBI, CNAIS and SGS standard, while those in soils of Cambic Podzol and Eutric Cambisol were 0.56 mg/kg and 1.13 mg/kg. Therefore, the feedstock selected for biochar production and especially for soil application should be seriously considered to mitigate the undesirable effects. Furthermore, the pyrolysis products of gas and liquid should be discharged effectively to avoid the unexpected contamination of biochar.

5. Packaging requirements

The eight packaging requirements mainly including registered trademark name and full street address, production date, weight of contents, application category and the place of production, standards compiled (if any), feedstock type and carbon content are required by SGS. The six packaging requirements of ANZBI are similar to SGS. The type of feedstock and carbon content must be stated on the packaging of biochar.

The six packaging requirements on label, packaging, transportation and storage required by CNAIS are required and should be in accord with GB 18382 and GB/T 8569 (CNS, 2009; CNS, 2021). The feedstock material and five basic properties relating to total carbon, fixed carbon, H/C, O/C and moisture content should be declared on the packaging.

There are no packaging requirements among the EBC, IBI and BQM. IBI indicated that the documentation of biochar feedstock and type (unprocessed or processed), thermochemical production parameters, as well as test results should be kept for seven years. EBC and BQM have requirements on quality assurance and certification of biochar producers to provide the approved certification and production records.

The packaging of biochar should be taken into account to prevent contamination risks when biochar is used in soil. It is of great importance that the type of feedstock, biochar production parameters and basic properties are labelled on the packaging bag to ensure sound and sustainable use of biochar.

6. Summary and future perspectives

There is a wide variety of biochar feedstock among six standards, while CNAIS requires the simple and specific feedstock source, which is derived from botanical waste biomass of agriculture and forestry. It is recommended that the feedstock and production temperature should be declared. Limiting the feedstock of biochar applied to soil would attach great importance to the safe production and sustainable use of biochar due to the wide range of feedstock limitations. The carbon content and H/C must be declared and meet with the threshold value while heavy metals including Hg, Cd, Pb, Ni, Cr, Cu and Zn, as well as polycyclic aromatic hydrocarbons are required by these six standards of biochar.

Biochar used in agriculture has the long-term potential to improve soil health, sequester carbon, and mitigate climate change. Therefore, its quality and safety need to be ensured through the establishment of biochar standard. The choice of feedstock, quality requirements, and standards for heavy metals and organic pollutants are essential for the safe and effective use of biochar. Additionally, the existing standards mainly focus on the quality of biochar products, and it is essential to develop relevant standard requirements for biochar production facilities, which play a critical role in biochar quality.

The properties tests and certification for biochar quality assurance would be straightforward and cost-effective if there were strict limits on feedstock and process temperature of biochar added to soil. It might be difficult for enterprises to afford the high cost of testing biochar properties if some properties with high testing costs need to be measured frequently during industrial production. Hence, enhancing the operability and feasibility of the standard would be of great importance, especially in the early stages of the development of the biochar industry. Moreover, the relatively few essential properties attaching great importance to the soil and alternative low-cost indicators of biochar could pave the way for the sustainable and effective implementation of the standard.

The biochar applications have gradually expanded, ranging from initial agriculture management to environment restoration, energy sources, and additives for a wide variety of applications. In recent years, non-agricultural applications of biochar have received considerable attention, and appropriate standards need to be taken into account for large-scale industrial application. Currently, the requirements on five applications of biochar are specified in Singapore, and it is recommended that the existing standards covering the essential applications of biochar should be progressively updated on the basis of extensive studies to provide an important reference for policy makers, biochar producers and biochar users.

Furthermore, biochar is a global issue because of its far-reaching implications for agriculture, environment and energy, and thus having a unified standard would be significant and environmentally beneficial. However, having the same standard in different countries would pose serious challenges in terms of available technology and economic development. Therefore, the mutual recognition of standards or the establishment of a globally recognised international biochar standard would facilitate the promising industrial ecosystem of biochar.

CRediT authorship contribution statement

Guiying Lin: Writing – original draft, Methodology, Data curation. **Yiying Wang:** Writing – review & editing, Methodology, Data curation. **Xiaodong Wu:** Methodology, Conceptualization. **Jun Meng:** Writing – review & editing, Methodology, Conceptualization. **Yong Sik Ok:** Methodology, Conceptualization. **Chi-Hwa Wang:** Writing – review & editing, Conceptualization.

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.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

References

Adekanye, T., Dada, O., Kolapo, J., 2022. Pyrolysis of maize cob at different temperatures for biochar production: Proximate, ultimate and spectroscopic characterisation. Res. Agr. Eng. 68, 27–34. https://doi.org/10.17221/106/2020-RAE.

Adhikari, S., Moon, E., Paz-Ferreiro, J., Timms, W., 2024. Comparative analysis of biochar carbon stability methods and implications for carbon credits. Sci. Total Environ. 914, 169607. https://doi.org/10.1016/j.scitotenv.2023.169607.

ANZBI, 2020. Code of practice for the sustainable production and use of Biochar in Australia and New Zealand Australia New Zealand Biochar Initiative. https://anzbig.org/wp-content/uploads/2020/07/ANZBI-Biochar-Code-of-Practice_2June2020_Draft.pdf. (Accessed 2 June 2020).

Bao, Z., Lotfy, V.F., Zhou, X., Fu, S., Basta, A.H., 2024. Assessment of porous carbon from rice straw residues with potassium ferrate-assisted activation as cationic and anionic dye adsorbents. Ind. Crop Prod. 212, 118298. https://doi.org/10.1016/j.indcrop.2024.118298.

Basta, A.H., Lotfy, V.F., Salem, A.M., 2022. Valorization of biomass pulping waste as effective additive for enhancing the performance of films based on liquid crystal hydroxypropyl-cellulose nanocomposites. Waste Biomass Valori. 13, 2217–2231. https://doi.org/10.1007/s12649-021-01631-7.

BQM, 2013. Biochar Quality Mandate v. 1.0: Version for public consultation. Edinburgh, United Kingdom. http://www.geos.ed.ac.uk/homes/sshackle/ BQM. pdf. (Accessed 14 July 2014).

Buss, W., Mašek, O., Graham, M., Wüst, D., 2015. Inherent organic compounds in biochar–their content, composition and potential toxic effects. J. Environ. Manage. 156, 150–157. https://doi.org/10.1016/j.jenvman.2015.03.035.

Chen, W., Meng, J., Han, X., Lan, Y., Zhang, W., 2019. Past, present, and future of biochar. Biochar 1, 75–87. https://doi.org/10.1007/s42773-019-00008-3.

CNAIS, 2022. Biochar. The Agricultural Industry Standard of the People's Republic of China; NY/T4159, pp. 1–9 (Accessed 11 July 2022).

CNS, 2009. Packing of solid chemical fertilizers. In: The State Standard of the People's Republic of China; GB 8569, pp. 1–5 (Accessed 30 November 2022).

CNS, 2021. Fertilizers marking-presentation and declaration. In: The State Standard of the People's Republic of China; GB 18382, pp. 1–8 (Accessed 30 April 2021).

Dixit, A., Ahammed, M.M., 2023. Use of modified biochar for removal of endocrine disrupting compounds from water and wastewater: a review. Bioresource Technol. Rep. 23, 101519. https://doi.org/10.1016/j.biteb.2023.101519.

EBC, 2012. European Biochar Certificate- Guidelines for a Sustainable Production of Biochar. European Biochar Foundation. http://www.european-biochar.org/biochar/media/doc/ebc-guidelines.pdf (Accessed 19 June 2015).

Enders, A., Hanley, K., Whitman, T., Joseph, S., Lehmann, J., 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresour. Technol. 114, 644–653. https://doi.org/10.1016/j.biortech.2012.03.022.

Gong, H., Zhao, L., Rui, X., Hu, J., Zhu, N., 2022. A review of pristine and modified biochar immobilizing typical heavy metals in soil: applications and challenges. J. Hazard. Mater. 432, 128668. https://doi.org/10.1016/j.jhazmat.2022.128668.

Hale, S.E., Lehmann, J., Rutherford, D., Zimmerman, A.R., Bachmann, R.T., Shitumbanuma, V., O'Toole, A., Sundqvist, K.L., Arp, H.P.H., Cornelissen, G., 2012. Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars. Environ. Sci. Technol. 46, 2830–2838. https://doi.org/10.1021/es203984k.

He, M., Xiong, X., Wang, L., Hou, D., Bolan, N.S., Ok, Y.S., Rinklebe, J., Tsang, D.C., 2021. A critical review on performance indicators for evaluating soil biota and soil health of biochar-amended soils. J. Hazard. Mater. 414, 125378. https://doi.org/10.1016/j.jhazmat.2021.125378.

Ho, P.H., Lofty, V., Basta, A., Trens, P., 2021. Designing microporous activated carbons from biomass for carbon dioxide adsorption at ambient temperature. A comparison between bagasse and rice by-products. J. Clean. Prod. 294, 126260. https://doi.org/10.1016/j.jclepro.2021.126260.

IBI, 2013. Standardized product definition and product testing guidelines for biochar that is used in soil: version number 1.1. International Biochar Initiative. https://biochar-international.org/wp-content/uploads/2023/01/IBI_Biochar_Standards_V1.1.pdf (Accessed 11 April 2013).

IBI, 2014. Standardized product definition and product testing guidelines for biochar that is used in soil: version number 2.0. International Biochar Initiative. https://biochar-international.org/wp-content/uploads/2023/01/ IBI Biochar Standards V2.0. pdf. (Accessed 27 October 2014).

IBI, 2015. Standardized product definition and product testing guidelines for biochar that is used in soil. International Biochar Initiative. https://biochar-international.org/wp-content/uploads/2022/03/IBI_Biochar_Certification_Program_Manual_V2.1_Final3.pdf (Accessed 23 November 2015).

Ippolito, J.A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J.M., Fuertes-Mendizabal, T., Cayuela, M.L., Sigua, G., Novak, J., Spokas, K., 2020. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. Biochar 2, 421–438. https://doi.org/10.1007/s42773-020-00067-x.

Islam, M.S., Kwak, J.-H., Nzediegwu, C., Wang, S., Palansuriya, K., Kwon, E.E., Naeth, M. A., El-Din, M.G., Ok, Y.S., Chang, S.X., 2021. Biochar heavy metal removal in aqueous solution depends on feedstock type and pyrolysis purging gas. Environ. Pollut. 281, 117094. https://doi.org/10.1016/j.envpol.2021.117094.

Iwuozor, K.O., Emenike, E.C., Omonayin, E.O., Bamigbola, J.O., Ojo, H.T., Awoyale, A. A., Eletta, O.A., Adeniyi, A.G., 2023. Unlocking the hidden value of pods: a review of thermochemical conversion processes for biochar production. Bioresource Technol. Rep. 22, 101488. https://doi.org/10.1016/j.biteb.2023.101488.

Lataf, A., Jozefczak, M., Vandecasteele, B., Viaene, J., Schreurs, S., Carleer, R., Yperman, J., Marchal, W., Cuypers, A., Vandamme, D., 2022. The effect of pyrolysis temperature and feedstock on biochar agronomic properties. J. Anal. Appl. Pyrol. 168, 105728. https://doi.org/10.1016/j.jaap.2022.105728.

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems–a review. Mitig. Adapt. Strat. Gl. 11, 395–419. https://doi.org/10.1007/s11027-005-9006-5.

Liu, Y., Weng, Z., Han, B., Guo, Z., Tian, H., Tang, Y., Cai, Y., Yang, Z., 2023. Recent studies on the comprehensive application of biochar in multiple environmental fields. J. Clean. Prod. 421, 138495. https://doi.org/10.1016/j.jclepro.2023.138495.

Major, J., Rondon, M., Molina, D., Riha, S.J., Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant and Soil 333, 117–128. https://doi.org/10.1007/s11104-010-0327-0.

Otoni, J.P., Matoso, S.C.G., Pérez, X.L.O., da Silva, V.B., 2024. Potential for agronomic and environmental use of biochars derived from different organic waste. J. Clean. Prod. 449, 141826. https://doi.org/10.1016/j.jclepro.2024.141826.

Qiu, B., Tao, X., Wang, H., Li, W., Ding, X., Chu, H., 2021. Biochar as a low-cost adsorbent for aqueous heavy metal removal: a review. J. Anal. Appl. Pyrol. 155, 105081. https://doi.org/10.1016/j.jaap.2021.105081.

Quilliam, R.S., Rangecroft, S., Emmett, B.A., Deluca, T.H., Jones, D.L., 2013. Is biochar a source or sink for polycyclic aromatic hydrocarbon (PAH) compounds in agricultural soils? GCB Bioenergy 5, 96–103. https://doi.org/10.1111/gcbb.12007.

Ruzickova, J., Koval, S., Raclavska, H., Kucbel, M., Svedova, B., Raclavsky, K., Juchelkova, D., Scala, F., 2021. A comprehensive assessment of potential hazard caused by organic compounds in biochar for agricultural use. J. Hazard. Mater. 403, 123644. https://doi.org/10.1016/j.jhazmat.2020.123644.

SGS, 2023. Singapore Standard, code of practice for production and application of biochar. Enterprise Singapore; SS698. https://www.singaporestandardseshop.sg/Product/SSPdtDetail/c39c65f7-15fa-42a8-a924-5079bdf25056. (Accessed 27 January 2025).

Sun, Q., Meng, J., Lan, Y., Shi, G., Yang, X., Cao, D., Chen, W., Han, X., 2021a. Long-term effects of biochar amendment on soil aggregate stability and biological binding agents in brown earth. Catena 205, 105460. https://doi.org/10.1016/j.catena.2021.105460.

Sun, Y., Xiong, X., He, M., Xu, Z., Hou, D., Zhang, W., Ok, Y.S., Rinklebe, J., Wang, L., Tsang, D.C., 2021b. Roles of biochar-derived dissolved organic matter in soil amendment and environmental remediation: a critical review. Chem. Eng. J. 424, 130387. https://doi.org/10.1016/j.cej.2021.130387.

Wang, D., Jiang, P., Zhang, H., Yuan, W., 2020. Biochar production and applications in agro and forestry systems: a review. Sci. Total Environ. 723, 137775. https://doi.org/10.1016/j.scitotenv.2020.137775.

Wang, Y., Lin, G., Li, X., Tai, M.H., Song, S., Tan, H.T.W., Leong, K., Yip, E.Y.B., Lee, G.Y. C., Dai, Y., 2023. Meeting the heavy-metal safety requirements for food crops by using biochar: an investigation using sunflower as a representative plant under different atmospheric CO_2 concentrations. Sci. Total Environ. 867, 161452. https://doi.org/10.1016/j.scitotenv.2023.161452.

Wu, P., Ata-Ul-Karim, S.T., Singh, B.P., Wang, H., Wu, T., Liu, C., Fang, G., Zhou, D., Wang, Y., Chen, W., 2019. A scientometric review of biochar research in the past 20 years (1998–2018). Biochar 1, 23–43. https://doi.org/10.1007/s42773-019-00002-9.

Yang, X., Kang, K., Qiu, L., Zhao, L., Sun, R., 2020. Effects of carbonization conditions on the yield and fixed carbon content of biochar from pruned apple tree branches. Renew. Energ. 146, 1691–1699. https://doi.org/10.1016/j.renene.2019.07.148.

Zuo, W., Wang, S., Zhou, Y., Ma, S., Yin, W., Shan, Y., Wang, X., 2023. Conditional remediation performance of wheat straw biochar on three typical Cd-contaminated soils. Sci. Total Environ. 863, 160998. https://doi.org/10.1016/j.scitotenv.2022.160998.