Chapter 8
Sewage Sludge Biochar

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Abstract The global production of sewage sludge (SS) has accompanied population growth and the expansion of global sewage treatment rates. Sewage sludge is a solid waste rich in nutrients, mainly N, P, Ca, Mg, and Zn. However, SS can also have high contaminating potential. Pyrolysis is an effective technological alternative to transform SS into an agricultural input. The solid product of SS pyrolysis is called SS biochar. In this chapter, we present the state of the-art of SS use in agriculture, highlighting benefits, limitations, and perspectives. Furthermore, we review innovative approaches to render SS biochar production and applicability more efficient and socially acceptable. Such approaches include: (a) SS biochar enrichment technologies; (b) SS biochar for plant disease control; and, (c) SS biochar for soil carbon sequestration. The risks of contamination with heavy metals from SS biochar were also discussed. Finally, recommendations were elaborated for improving the multiple uses of SS biochar in agriculture.

8.1 Introduction

Sewage sludge (SS) is an urban waste generated during wastewater treatment. Globally an estimated 9.5 million m^3 of human sewage and 900 million m^3 of municipal wastewater are produced every day (Mateo-Sagasta et al. 2015). Several alternatives have been used to transform SS into a suitable product to be applied in agriculture. Among them, thermal treatments such as incineration, gasification, hydrothermal carbonation, and pyrolysis belong among the suitable solutions of SS disposal (Racek et al. 2020).

Thermal processing of SS by pyrolysis represents an important alternative to allow for agricultural use of this residue and presents advantages such as reduction of

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volume and transport costs in addition to the elimination of undesirable microorganisms (Paz-Ferreiro et al. 2018). Biochar is a solid, carbon rich product obtained by heating biomass under limited oxygenation conditions, in a process known as pyrolysis (Sohi 2012). Despite increasing the concentration of total heavy metals in relation to the raw material, pyrolysis reduces the bioavailability of several metals (Figueiredo et al. 2019a, b; Chagas et al. 2021a). In addition, the application of biochar to the soil has an alkalinizing effect (Hossain et al. 2011), increases the accumulation of total carbon (C) and soil organic matter pools (Chagas et al. 2022), and can reduce phosphorus (P) adsorption (Cui et al. 2011).

Although few studies have been performed in tropical regions (Sousa and Figueiredo 2016; Faria et al. 2018; Figueiredo et al. 2018a, b, 2020), the benefits of SS biochar are already clear with regard to the supply of multiple plant nutrients for several crops (Sousa and Figueiredo 2016; Faria et al. 2018). Recently, studies have shown positive effects of SS biochar on the control of plant pathogens (de Araujo et al. 2019a) and in increasing the use efficiency of N from mineral fertilizers (Figueiredo et al. 2020).

There is still a significant shortage of information on the advantages and limitations of using biochar from sewage sludge on agricultural land. Therefore, this chapter summarizes the main approaches applied to the SS biochar as a soil amendment, including advantages, limitations, and perspectives.

8.2 State of the Art

8.2.1 Sewage Sludge in Agriculture: Benefits and Limitations

As biomass rich in carbon and nutrients, SS can be used for different purposes, emphasizing disposal in agricultural areas, land reclamation, landscaping, forestry, industrial processes, power generation, civil construction, and biochar production. Furthermore, SS may be destined for incineration or landfill (Fig. 8.1). In agriculture,

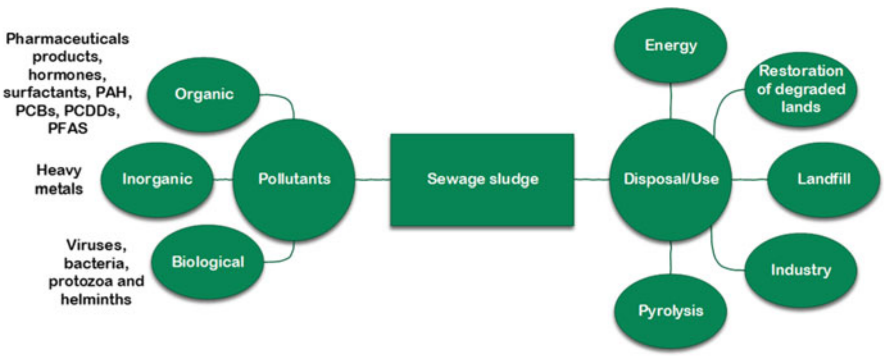

Fig. 8.1 Disposal alternatives and major contaminants present in the sewage sludge

SS can be used as a fertilizer or as a soil conditioner. It is estimated that the municipal wastewater produced globally contains enough nutrients to replace 25% of the nitrogen currently used to fertilize agricultural land in the form of synthetic fertilizers, and 15% of the phosphorus (Andersson et al. 2016). Alternatives such as prolonged alkaline stabilization, adopted in the state of Paraná, Brazil, have been successful among farmers, despite a limited adoption (Souza et al. 2008). In this process, the pH of the sludge is raised to 12 by adding large amounts of lime. The monitoring of pollutants in the sludge and in the soil is required, in addition to complications which include logistics of transporting the sludge, uneven demand over the year (concentrated in two growing seasons), and the high number of rainy days, which present challenges for practical application.

Despite the advances in research and government actions in recent decades, the use of SS worldwide is still very limited, particularly in developing countries that lack efficient sewage treatment systems (Andersson et al. 2016). As a result of the precautionary principle, legislation dealing with the use of SS imposes several restrictions on the agricultural use of this waste. Figure 8.1 shows the main pollutants present in SS, such as organic compounds, inorganic and biological components. Several types of organic chemicals, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and perfluoroalkyl substances (PFAS) may be found in treated SS (Paz-Ferreiro et al. 2018).

The presence of these contaminants with values above the limits established in specific legislation makes SS unfit for use in agricultural areas because of its high potential for contamination of the environment and the food chain (Collivignarelli et al. 2019). As a consequence of restrictions for their use, large amounts of SS accumulate in drying yards or are disposed of in dumps and water courses. With the lack of planning for the sustainable use of SS, major sanitary and environmental problems have been witnessed in many cities around the world.

Among the alternatives to make use of SS in agriculture feasible, thermal processing by pyrolysis has received much attention from researchers in the last decade (Paz-Ferreiro et al. 2018; Patel et al. 2020; Chagas et al. 2021a). Pyrolysis produces a solid material called biochar that can be used in agriculture, as well as biogas and bio-oil that can be used as an alternative energy source (Patel et al. 2020). In the specific case of SS the pyrolysis transformation eliminates pathogens and degrades potentially damaging organic compounds (Devi and Saroha 2013), thus permitting that SS be used for nutrient cycling and C accumulation in the soil.

8.2.2 Pyrolysis as a Sustainable Alternative to Enable the Disposal of Sewage Sludge on Agricultural Soil

8.2.2.1 Chemical Characteristics of Sewage Sludge Biochar

Compared with other urban wastes, SS biochars present high levels of nutrients such as P, N, Ca, and Mg (Figueiredo et al. 2018b), and when applied to tropical soils they are able to substitute soluble chemical fertilizers used in the production of different crops (Sousa and Figueiredo 2016; Faria et al. 2018; Fachini et al. 2021a, b; Chagas et al. 2021b).

The concentration of nutrients in the SS biochar is dependent on factors such as the type of treatment applied to the sewage and pyrolysis conditions such as temperature and residence time. Sludge that undergoes tertiary treatment, using methods for precipitation of N and P, is rich in these nutrients and poor in those that are removed together with water, such as potassium.

Figure 8.2 shows the macronutrient contents of sewage sludges and biochars produced at 300 and 500 °C. Overall, the pyrolysis of SS enriches the macronutrients in the biochars. The significant increase in phosphorus content with the pyrolysis temperature is a good characteristic considering that soils from tropical regions usually have a very low content of this nutrient. Despite increasing nitrogen contents up to 300 °C with decreases at higher temperatures, generally pyrolysis reduced the concentrations of nitrate and ammonium from the feedstock (Figueiredo et al.

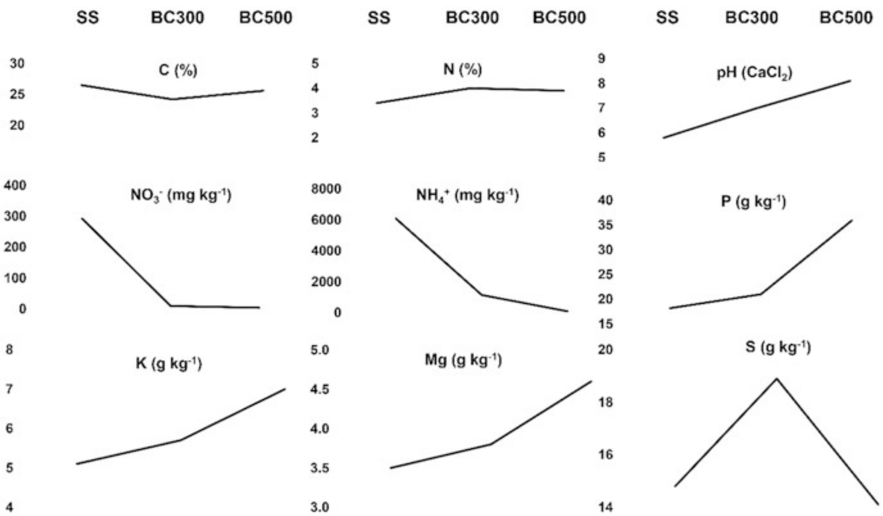

Fig. 8.2 Characteristics of sewage sludge (SS) and biochars produced at 300 °C (BC300) and 500 °C (BC500). Mean values estimated from Mierzwa-Hersztek et al. (2018); Chagas et al. (2021b), Tian et al. (2019); Gonzaga et al. (2018); Jafari Tarf et al. (2021); Khanmohammadi et al. (2015); Khan et al. (2015); Yuan et al. (2013); Zhang et al. (2015); Figueiredo et al. (2018a); Yuan et al. (2015); Méndez et al. (2012)

2018b). This decrease may be a result of nitrogen transformation to pyridine and pyrrols during pyrolysis, especially above 300 °C. Nevertheless, the concentration of ammonium in BC300 is 30 times higher than those normally found in acid soils from tropical regions (Nascente et al. 2012). As the pyrolysis temperature increases the biochar becomes more alkaline highlighting its function to act as a soil acidic neutralizer.

8.2.2.2 Sewage Sludge Biochar as Soil Amendment

Sewage sludge biochar can act as a soil amendment improving the chemical, physical, and biological properties (Fig. 8.3). Among the nutrients provided by SS biochar obtained after tertiary treatment, P was highlighted by its great availability in the soil and high absorption by the crops (Faria et al. 2018; Figueiredo et al. 2021). It is currently well known that SS biochar is a source of P, potentially replacing soluble mineral fertilizers. However, studies on the dynamics of P and the microbiota related to its cycling in the soil under application of SS biochar are incipient (Figueiredo et al. 2019b) and this represents an important scientific gap, since the efficiency of phosphate fertilization in tropical soils with high capacity of P adsorption is very low.

Sewage sludge biochar may also indirectly improve nutrient use efficiency by plants. For example, the beneficial effect of the interaction of biochar with plant growth-promoting microorganisms such as mycorrhizal fungi has been demonstrated. Hammer et al. (2014) concluded that hyphae of arbuscular mycorrhizal fungi can access biochar micropores that are too small for the penetration of most plant roots (<10 μm) and may therefore mediate plant uptake of P present in the

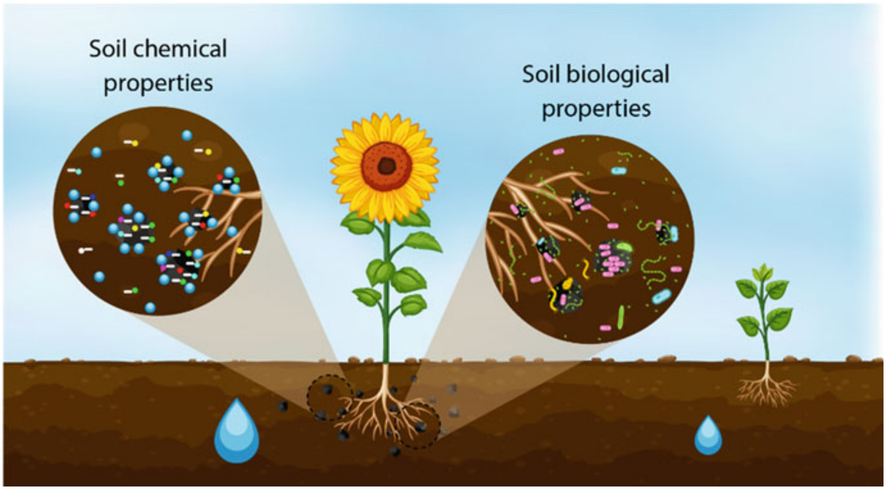

Fig. 8.3 Schematic of the action of sewage sludge biochar on the soil chemical and biological properties

biochar. Thus, the functions of arbuscular mycorrhizal fungi and biochar can contribute to the sustainability of weathered soils, deficient in available P under natural conditions, such as those that predominate in tropical soils.

The exclusive application of SS biochar or combined application with chemical fertilizer (NPK) increased corn productivity for two consecutive harvests in tropical soils (Faria et al. 2018). According to these authors, with the exception of potassium, the 15 Mg ha^{-1} dose of biochar was able to provide all nutrients in sufficient quantity to promote corn yields of 10 Mg ha^{-1} in tropical acid soil from the central region of Brazil. Residual effects of SS biochar on soil nutrient contents remained up to 3 years after stopping biochar application (Chagas et al. 2021b).

8.2.2.3 Sewage Sludge Biochar for Plant Disease Control

Studies on the use of biochar to control plant diseases have grown in recent years (Kumar et al. 2018; Liu et al. 2019; de Araujo et al. 2019a; Jaiswal et al. 2020). Biochars are able to control plant diseases caused by fungi, bacteria, or viruses (Jaiswal et al. 2020; Zhang et al. 2017a, b; Wang et al. 2018). However, most studies have focused on the effects of biochar on the control of fungal diseases (Wu et al. 2020; Wang et al. 2019; Kolton et al. 2017). Among the phytopathogenic fungi evaluated, the genus *Fusarium* stands out (Jaiswal et al. 2020; Wu et al. 2020; Liu et al. 2019). The diseases caused by this genus were the most suppressed by biochar application (Jaiswal et al. 2018; Rogovska et al. 2017).

Biochar has direct and indirect effects on the pathogen or disease. The most often reported effects are: reduced disease rate (Wang et al. 2020); inhibition of mycelial growth (Wu et al. 2020); reduced pathogen virulence (Wu et al. 2020); delay in the spread of the disease (Sabes et al. 2020); pathogen suppression (Wang et al. 2019); reduced plant susceptibility to disease (Kolton et al. 2017); greater plant resistance to the disease (Dai et al. 2017); reduction of root infection rate; and reduced disease severity (Rogovska et al. 2017).

Feedstocks commonly used to produce biochar suitable for plant diseases control are: wood and its derivatives (wood chips/barks, sawdust) (Jaiswal et al. 2019; Heck et al. 2019), vegetable residues used in the greenhouse (Jaiswal et al. 2020), and rice straw/husk (Wu et al. 2020; Sabes et al. 2020). A wide range of pyrolysis temperatures can be used for this purpose (300–1000 °C) (Marra et al. 2018; Atucha and Litus 2015). However, the highest plant disease control rates were obtained with biochar produced at pyrolysis temperatures ranging from 350 to 600 °C (Jaiswal et al. 2018; Lu et al. 2016a, b).

The dose of biochar is also an important factor for effective disease control. The best results were obtained when biochars were applied at doses ranging from 0 to 5% (de Araujo et al. 2019a). Furthermore, there is a certain specificity between the type and dose of biochar and the type of pathogen. Thus, each material can have an optimal dose with greater impact on the disease (Liu et al. 2019).

Recent studies have indicated that biochar from SS is also capable of controlling soilborne pathogenic fungi that infect various types of crops (de Araujo et al. 2019a, b). As a consequence of disease control, SS biochar promoted higher productivity of crops such as beans (de Araujo et al. 2019a) and soybeans (de Araujo et al. 2019b). These studies also indicated a synergistic effect between SS biochar and beneficial microorganisms such as *Trichoderma* spp. to control pathogenic fungi and increase crop productivity. Despite this potential, the use of SS biochar to control pathogens still needs to be better studied under field conditions and with a wide variety of pathogens and host plants.

8.2.2.4 Biochar Enrichment

Biochar enrichment techniques have allowed to obtain biochar-based fertilizers, with great potential to improve soil fertility (Lustosa Filho et al. 2020). According to Ndoung et al. (2021), there are three methods to enrich biochar with nutrients: (i) direct treatment method, (ii) pre-treatment method, and (iii) post-treatment method. In the direct treatment method, nutrient-rich feedstocks are submitted to slow pyrolysis (Ndoung et al. 2021). In the pre-treatment method, the feedstock is treated with nutrient-rich materials before undergoing pyrolysis. In this method, feedstocks may be enriched with chemical fertilizers, organic wastes, or agro-industrial residues. In the post-treatment method, several products can be used to composite enriched biochar after the pyrolysis process. In this process, biochars are mixed with a nutrient-rich source, including chemical fertilizers, clays, ground rock, composts, wastewater, etc.

Biochar enrichment may be produced from a wide variety of possibilities and combinations (Ndoung et al. 2021). Significant success has been obtained by enriching biochar with nutrients such as P (Lustosa Filho et al. 2020; Carneiro et al. 2021), N from urea (Shi et al. 2020), sulfur (Zhang et al. 2017a, b), and iron (Dad et al. 2021). Among the post-treatment (post-pyrolysis) methods, the granulation and pelleting processes of biochar are the most commonly used for nutrient enrichment (Ndoung et al. 2021). They have been used to minimize the risk of dust and respiratory problems caused by the application of biochar in powder form (Vincevica-Gaile et al. 2019). Specific characteristics of feedstock should be considered in biochar enrichment. For sewage sludge biochar, for example, an interesting strategy is enrichment with potassium, since this nutrient is present in low concentration in SS and, consequently, in the biochar. Furthermore, the high adsorptive capacity of biochar can retain K (Fachini et al. 2021b), acting as a slow-release fertilizer, thus reducing the loss of this nutrient through leaching. Figure 8.4 shows an alternative technological process to produce K-enriched SS biochar in the form of granules and pellets.

Enriched biochars can improve soil chemical and biological properties, nutrient use efficiency and increase crop productivity compared to mineral fertilizers and

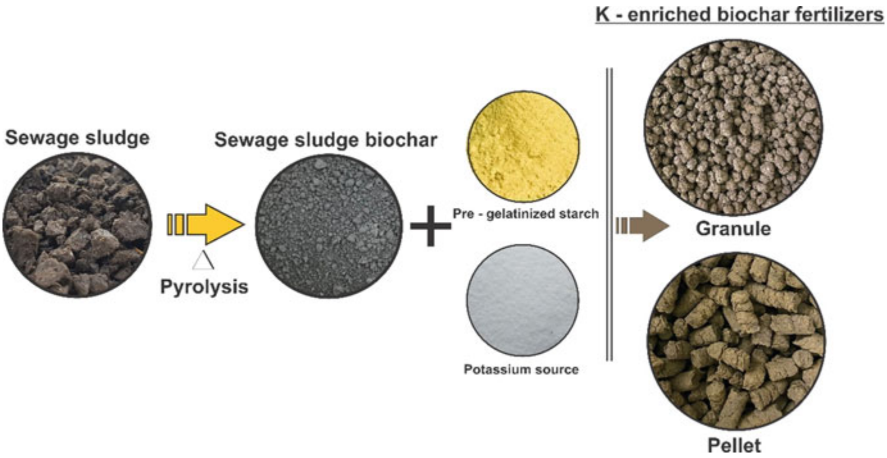

Fig. 8.4 Steps to produce enriched fertilizers from sewage sludge biochar

biochars applied separately (Ndoung et al. 2021). According to these authors, the application of a P-enriched biochar increased soil P and N contents. In addition to increasing the concentration of P, the application of P-enriched biochar also increased soil chemical properties such as pH and CEC (Carneiro et al. 2021). The main mechanism that explains the greater efficiency of a biochar-based fertilizer is the way in which the enriched nutrient is released. Biochar-based fertilizers differ from other fertilizers in their ability to gradually release nutrients into the soil, acting as a slow-release fertilizer (Lustosa Filho et al. 2020), increasing efficiency by reducing losses due to leaching or volatilization (Gwenzi et al. 2016).

8.2.2.5 Sewage Sludge Biochar and Carbon Sequestration in the Soil

The nutritional performance of biochar produced from several feedstocks is widely known. According to Zimmerman et al. (2011), biochar is also capable of increasing soil C stocks mainly in stable forms of organic compounds. This is possible since pyrolysis alters the feedstock promoting C buildup in the final biochar (Novotny et al. 2015). Therefore, when used as a soil amendment, biochar can sequester C in the soil (Figueiredo et al. 2018a; Chagas et al. 2022) and reduce greenhouse gas emissions from agricultural activities (Chagas et al. 2022; Plaza et al. 2016). According to Woolf et al. (2010), adopting biochar technology could compensate up to 12% of global CO_2 emissions into the atmosphere.

In general, biochars obtained at lower temperatures around 300 °C have fewer aromatic structures than those obtained at higher temperatures (≥500 °C) (Al-Wabel et al. 2013; Figueiredo et al. 2018a). This difference in the organic matrix of the biochars exerts a strong influence on the nutrient mineralization rate and on the long-term accumulation of C (Al-Wabel et al. 2013). Recently, Chagas et al. (2022), using results from a global meta-analysis, concluded that biochar increases several types of SOM fractions. Among these fractions, the most labile and active fractions such as microbial biomass, labile C, and easily oxidizable C are most sensitive to the changes promoted by crops (Cambardella and Elliott 1992). On the other hand, the stable fractions such as humic substances represent more recalcitrant forms of SOM, whose changes occur over a longer period of time (Figueiredo et al. 2018b).

Despite substantial advances in biochar knowledge in recent years, there are still many questions regarding its real short- and long-term impacts and how it acts on the soil (Cernansky 2015). Of the few works performed under field conditions with SS biochar application for consecutive years, Figueiredo et al. (2018a) concluded that the pyrolysis temperature is the driving factor in the function of biochar to increase organic C in the soil. In general, biochar produced at lower temperatures (around 300 °C) can increase labile fractions. On the other hand, when made at higher temperatures (≥500 °C), biochars increase recalcitrant SOM pools.

8.2.2.6 Sewage Sludge Biochar and the Risks of Contamination with Heavy Metals

Sewage sludge has heavy metal (HM) contents that vary depending on the origin (industrial, urban, or mixed) and the treatment that the sewage receives (Fytili and Zabaniotou 2008). Wang et al. (2008) reported that the application of SS from mixed-source sewage treatment (urban, commercial, and industrial) in China increased the concentration of heavy metals in the soil at all doses utilized (15–150 Mg ha^{-1}).

Chemical composition of the biomass used in pyrolysis is directly related to the HM concentration in the biochar obtained. Biochar produced from several feedstocks (e.g., wood, rice straw, animal manure) generally shows low levels of heavy metals, since these are not part of their natural composition (Park et al. 2011; Bian et al. 2014; Lucchini et al. 2014). However, in the case of SS the presence of HMs in the biochar is dependent on the type of sewage that makes up the sludge (domestic, industrial, or mixed). This dependence results in SS biochars with distinct HMs concentrations (Chagas et al. 2021a, b). For example, the municipal SS biochar submitted to secondary treatment showed a HM content suitable for agricultural use according to the local regulations of Guiyang, China (Liu et al. 2014). However, Van Wesenbeeck et al. (2014) observed that even on Oahu, a small island located in Hawaii, the HM contents in SS varied significantly between communities and over the years.

During pyrolysis, most metals including Pb, Ni, Cu, Zn, and Cr are retained in the biochar (solid fraction), since they present boiling points higher than the temperature normally used in pyrolysis (Van Wesenbeeck et al. 2014; Lu et al. 2016a, b). Thus, pyrolysis concentrates total HMs in the biochar (Lu et al. 2016a, b; Kameyama et al. 2017; Figueiredo et al. 2019a, b), and depending on the HM contents present in the

SS may make its use unviable for agricultural purposes (Chagas et al. 2021a, b). The higher the pyrolysis temperature used, the higher the concentration of total HMs in the biochar (Yuan et al. 2015; Lu et al. 2016a, b). However, when using temperatures >600 °C, some heavy metals such as Cd volatilize and leave the reactor together with the produced gases. Below 600 °C the small heavy metal losses observed are mainly due to the escape of charged fine metal particles carried in the gas outflow (Kistler et al. 1987).

Even when there is an increase in the concentration of HMs during pyrolysis, it is observed that when applied to the soil, biochar affects the behavior of these metals, reducing their solubility, availability, transport, and spatial distribution (Zhou et al. 2017). Thus, with the application of SS biochar there is a reduction of the HM levels available in the soil, with values lower than those present with the use of sewage sludge (Figueiredo et al. 2019a, b; Chagas et al. 2021a, b).

Table 8.1 summarizes the effects of SS biochar on total and available HM in the soil and plant. Even when applying SS biochar with total HM contents below the local regulated limits, all studies shown in Table 8.1 that assessed the HM content in soils after SS biochar application reported accumulation of at least one of the analyzed HMs in the soil. In general, SS biochar increases the total HM content but decreases the available HM in the soil and the rate of HM uptake by plants.

In the specific case of SS biochar of predominantly domestic origin, in the central region of Brazil, Figueiredo et al. (2019a, b) concluded that with the increase in pyrolysis temperature there is reduced availability of these HMs, with values below 5.2% in relation to the total contents. Even with the application of 15 Mg ha^{-1} of SS biochar, the total and available contents in the soil were similar to the control treatment, without biochar application, 1 year after its application. Recently, Chagas et al. (2021a, b) proved that this low HM contents in soil amended with SS biochar may remain for at least 5 years.

8.3 Recommendations

Despite the potential benefits of SS biochar as an agricultural input, some aspects still need to be considered in future studies. Further information from long-term experiments is crucial. Production or co-production of biochar in combination with other feedstocks/materials such as soil remineralizers and organomineral fertilizers should be studied. Furthermore, identify additional benefits of biochar (plant disease and pest management/control) should be improved. Finally, studies on the energy efficiency of the SS pyrolysis process need to be broad.

Table 8.1 Sewage sludge/biosolids effects on total and available heavy metal (HM) in soil and plant

Reference	Crop	Pyrolysis temperature (°C)	Dose of biochar	Soil texture	Soil pH	Total HM								Available HM								Leaf content/HM uptake							
						As	Cd	Cr	Cu	Mn	Ni	Pb	Zn	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
[1]	Rice	550	5%	S	4.9									↓	↑	↓	↑		↓	↓	↑	↓	↑	↓	–		↓	↓	↑
	Rice	550	10%	S	5.4									↓	↑	↓	↑		↓	↓	↑	↓	↑	↓	–		↓	↓	↑
[2]	Corn	350	7.3 t ha^{-1}	M	7.5–7.6												–	–		↓	↑				–	–		↓	–
	Corn	350	14.5 t ha^{-1}	M	7.5–7.6												–	–		↓	↑				↓	–		↓	–
	Corn	350	29 t ha^{-1}	M	7.5–7.6												–	–		↓	↑				↓	↓		↓	↓
[3]	Rice	800	20 t ha^{-1}	M	7.9		↑		–			↑	↑		↓		–			↓	–		–		–			–	–
	Wheat	800	20 t ha^{-1}	M	7.7		↑		–			↑	↑		–		↑			–	↓		–		–			↓	–
[4]	Grass	300	5%	M	8.6	↑	↑	–	↑	↑		↑	↑										↓	–	↓	↓		↓	↓
[5]	Cucumber	550	2%	S	7.3–7.6									↓	–		–			↓	–	↓	↑		–			↓	↓
	Cucumber	550	5%	S	7.4–7.5									↓	–		–			↓	–	↓	↑		–			↓	↓
	Cucumber	550	10%	S	7.4–7.6									↓	–		↓			↓	–	↓	↑		↓			↓	↓
[6]	Grass	500	5%	M	8.6	↑	↑	↑	↑			↑	↑									–	↓	↓	↓			↓	↓
[7]	–	500	4%	M	7.8										–		↑		↑	–	–								
	–	500	8%	M	7.8										–		↑		↑	–	–								
[8]	Corn	300	15 t ha^{-1}	C	4.8			–	–	↑		–	–			–	–	–		–	↑								
	Corn	500	15 t ha^{-1}	C	5.1			–	–	–		–	–			–	–	–		–	↑								
[9][a]	Beans	550	4%	–	5.7									↓	↓	↓			↓	↓	↑	↓	↓	↓			↓	↓	↑
[10]	Corn	350	0.5%	–	6.2																		↑				–	↓	–
[11]	Corn	300–500	15 t ha^{-1}	C	6.7				–		–	↑	–												↑		–	↑	↑
[12]	Corn	300	15 t ha^{-1}	C	4.8																				↑	↑			↑
	Corn	500	15 t ha^{-1}	C	5.1																				↑	↑			↑

(↑), (—), and (↓) mean that biochar application increases, maintains, or decreases, respectively, compared to the control (with no biochar)
[a]Contaminated soil by HM
S sandy; *M* medium; *C* clayey

(continued)

References: [1] Khan et al. (2013); [2] Khanmohammadi et al. (2017); [3] Shao et al. (2019); [4] Tian et al. (2019); [5] Waqas et al. (2014); [6] Yue et al. (2017); [7] Méndez et al. (2012); [8] Figueiredo et al. (2019a, b); [9] Ibrahim et al. (2017); [10] Huang et al. (2017); [11] Gwenzi et al. (2016); [12] Faria et al. (2018)

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