Research Article

Biochar Derived from Domestic Sewage Sludge: Influence of Temperature Pyrolysis on Biochars’ Chemical Properties and Phytotoxicity

Rahma Inès Zoghlaami,1 Sarra Hechmi,2 Rihab Weghlani,1 Naceur Jedidi,2 and Mohamed Moussa1

1AridRegionInstitute,Eremology and Fight Against Desertification Laboratory (LR016IRA01), University of Gabes, Medenine 4119, Tunisia
2WaterResearchandTechnologyCenter,University of Carthage,P.O. Box 273, Soliman 8020, Tunisia

Correspondence should be addressed to Rahma Inès Zoghlaami; inesrahma.zoghlaami@gmail.com

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The pyrolytic conversion of domestic sewage sludge (SS) into biochar is a promising method to reduce its large volume and recycle its high-value fuel gas as renewable energy and the use of its chemicals as soil fertilizers. Even though the effects of pyrolysis temperature on energy recovery have been extensively studied, little information has been found on nutrient recovery and biochar’s phytotoxicity before its reuse as a soil amendment. This study aims to investigate the ideal pyrolysis temperature that guarantees higher fertility levels as well as meeting quality standards for land disposal. Accordingly, air-dried domestic sewage sludge has been pyrolyzed at 260°C (PSS1), at 420°C (PSS2), and at 610°C (PSS3) with a residence time of 20, 40, and 60 minutes, respectively. The raw sewage sludge and the produced biochars have been analyzed to determine their volatile organic matter (VOM), mineral content (MC), nutrients’ level (total nitrogen TN, available phosphorus P, and potassium K), alkalinity (pH), and salinity (electrical conductivity EC and Na). The toxic effect of biochars derived from SS has been evaluated through the analysis of trace metals (Pb, Cr, Cd, Cu, and Zn) and their toxicity by measuring root elongation inhibition (REI). As expected, pyrolysis temperature has a significant impact on the biochars’ characteristics. This has been justified by higher VOM, TN, and P in the sewage sludge (SS) and the biochar (PSS1) produced at low temperature (260°C). However, higher pH, EC, Na, and K have been found in the biochars (PSS2 and PSS3) produced at higher temperature (420 and 610°C). The effect of pyrolysis temperature on trace metals concentrations has shown different patterns from one element to another, which indicates lower levels in the biochar (PSS2) produced at 420°C. As a result, the lowest REI has been observed in PSS2 compared to that in SS, PSS1, and PSS3, which highlights that 420°C is the ideal pyrolysis temperature for the safe reuse of SS as a soil amendment.

1. Introduction

The US Environmental Protection Agency [1] defines domestic sewage sludge (SS) as a byproduct generated from the wastewater treatment process and refers to them as biosolids [2]. The production of domestic sewage sludge increases with population growth, urbanization, rapid industrialization, and changes in consumption [3]. SS is a potential source of valuable resources and energy [3, 4]. Since sludge has high organic matter content and is rich in nutrients [5, 6], it can be used as a fertilizer/soil amendment for vegetable crops, horticultural plants, and forests [7]. Once applied to the soil, SS can improve soil fertility level [6, 8, 9] and enhance plant growth [10], particularly in arid and semiarid regions. SS may also contain potential toxic elements including salts [6, 11], trace metals [12], organic pollutants [13], and pathogenic organisms [14]. If it is not managed properly, it can negatively impact human health and the environment [1, 3, 15].
Pyrolysis is a thermochemical reaction carried out at elevated temperature (500–1000°C) and in an inert atmosphere. Depending on the operational conditions, pyrolysis can be aimed at obtaining liquid (bio-oil), gas (hydrogen), or solid (biochar) [16]. Biochar’s characteristics are highly dependent on the pyrolysis process conditions [17, 18]. Temperature is one of the most important parameters of the pyrolysis process that can significantly affect the chemical and physical properties of the biochar [19, 20] in terms of pore size distribution, functional groups, elementary composition, and the pH value [21]. At low temperature (200–400°C), the biochar yields a greater recovery of C and other nutrients (feedstock dependent), which are usually lost at higher temperature. Higher pyrolysis temperature results in an increase of surface area, carbonized fractions, pH, and volatile matter. Residence time is another important factor that affects the characteristics and production costs of the biochar [22]. Short residence time (of few minutes) can lead to incomplete charring of the raw material, which reduces the stability of the biochar, and the potential of carbon sequestration [23]. It is the most efficient method to produce biofuels for heat and energy generation [24]. Longer residence time (from 20 minutes to few hours) is instrumental for the biochar production with a typical yield of 35% of dry biomass weight [25]. Recent studies have shown the volatilization of some trace metals (i.e., Cd and Zn) after 30 minutes of residence time and the immobilization of Cu, Cr, Ni, and Pb in the biochar after 60 minutes of residence time [26].

Sewage sludge pyrolysis can be used as an effective low-cost technology to reduce its large volume [27, 28] and simultaneously recover its valuable byproducts [29]. The thermal decomposition of SS has been investigated since the 1980s for different purposes. Urban and Antal [30], Gonzalo [31], and Thipkhunthod et al. [32] have studied the kinetics of this thermal reaction and the composition of the noncondensable gases. Others have focused on the effect of pyrolysis conditions (temperature, residence time) on the yield and the properties of the obtained liquid [33, 34, 35]. Sewage sludge pyrolysis has been also investigated to obtain a solid adsorbent (biochar) that can be used for water treatment and pollutant immobilization [36, 37].

Recently, it was demonstrated that SS pyrolysis can cause the thermal breakdown of pathogens and some toxic organic compounds [38, 39], required for possible land application [40, 41]. Consequently, biochar derived from SS can have a significant impact on the physical, chemical, and biological properties of depleted soils without posing a risk of contamination [42, 43]. As it is known, most of the studies have focused on the yield rate, the elemental composition (C, H, O, N), the mineral content (ash), the pH, the specific surface area, and metal content [44–47]. However, the effects of pyrolysis temperature on the nutrient status (total C and N and available P and K) and the salinity level (EC, Na) of the resulting biochar are scarce. The evaluation of the biochar toxicity is also extremely important for screening the suitability of the biochar before its land application. A series of ecotoxicological assays, using selected organisms, can be assessed to determine lethal and sublethal effects of complex materials like biochars [48]. The assessment of root elongation inhibition is one of the most sensitive ecological parameters used to monitor the response of plant seeds exposed to potential pollution [48–50]. The use of lettuce seeds has been recommended thanks to their rapid germination and sensitivity to low concentrations of phytotoxic substances [49, 51]. Previous studies have reported the use of eucalyptus (Eucalyptus grandis L.) [52] and wheat (Triticum aestivum) [53], whereas the use of lettuce seeds, which is the most sensitive plant, has not been highlighted. Thus, this study may be the first to focus on this point. The objective of this work is to determine the effects of pyrolysis temperature (260, 420, and 610°C) on the characteristics of an air-dried sewage sludge collected from an urban wastewater treatment plant. The focus of this study is on the produced biochars that will be used as a soil amendment. The change in the nutrient status, salinity level, metal content under the selected temperatures of pyrolysis is investigated, taking into account biochar toxicity using lettuce seeds.

2. Materials and Methods

2.1. Sewage Sludge Collection and Biochar Preparation. The domestic sewage sludge has been obtained from a municipal (mechanical-biological) wastewater treatment plant (WTTP) located in Medenine (South-eastern, Tunisia) (33°21′17″N 010°30′19″E). SS has been generated by an activated sludge treatment process followed by dewatering using drying beds. Three samples of sewage sludge were randomly collected from the surface bed during winter 2019 and then homogenized into a composite sample according to Lacorte et al. [54]. In the laboratory, SS pyrolysis has been assessed in a furnace (Nabertherm), where 500 ml of nitrogen has been added at every pyrolysis process to maintain an anoxic environment as recommended by Mohammed et al. [55] and Ye et al. [56]. SS has been pyrolyzed at 260°C (PSS1), 420°C (PSS2), and 610°C (PSS3) for 20, 40, and 60 minutes, respectively, with a heating rate of 10°C·min⁻¹. The raw SS has been used as a control, and all treatments have been performed in five replicates. After pyrolysis, SS samples (raw and biochars) were cooled down to room temperature, passed through a 2 mm mesh sieve, and stored before analysis [54].

2.2. Physical and Chemical Characterization of the Raw Sewage Sludge and the Produced Biochars. The pH and electrical conductivity (EC) have been determined in sample-water extracts at a ratio of 1:5 and 1:2.5, respectively, after shaking for 2 hours.

The volatile organic matter (VOM) has been calculated based on the air-dried weight according to the following equation:

\[ \text{VOM} \% = 100 - \text{MC}, \]

where MC is the mineral content determined according to Yong et al. [57]. Firstly, air-dried samples have been weighed
and then combusted in a furnace at 560°C for 6 hours. The final weight has been recorded using the same calibrated analytical balance. MC has been calculated using the following equation:

$$MC(\%) = \frac{m_2}{m_1} \times 100,$$

where $m_1$ and $m_2$ are the weight of the air-dried and the combusted sample, respectively.

Total nitrogen (TN) has been determined according to the Kjeldahl method [58]. Available phosphorus “orthophosphate” (P) has been determined by the colorimetric method at 430 nm according to ISO [59]. Exchangeable bases (Na⁺ and K⁺) have been extracted from the biochar with HCl (6N) and measured by atomic adsorption [60]. Trace metals (Cu, Cd, Zn, Pb, and Cr) were determined by mixing 0.5 g of samples with HCl and HNO₃ (5 mL each) [61]. After acid digestion, the mixtures have been filtered and measured using atomic absorption spectrometry (AAS) equipped with a graphite oven (Perkin Elmer Instruments, USA).

2.3. Phytotoxicity Test. The phytotoxicity assay has been done in Petri dishes of 15 mm diameter using lettuce seeds (Lactuca sativa L.). Sample solutions have been prepared by dissolving 1 gram of the sample in 100 ml of distilled water and then filtered before their use. After that, filter papers (Whatman no. 3) have been placed in Petri dishes and humidified with 9 ml of the prepared sample solution. 9 ml of distilled water has been used as control. Subsequently, 20 lettuce seeds have been placed on top of the paper filter. Petri dishes have been covered and incubated in the dark at 25°C for 7 days. At the end of the incubation period, germinated plantlets have been meticulously uprooted and the numbers of germinated seeds have been counted and the lengths of the roots have been measured [48]. To provide an integrative interpretation of the measurements, seed germination and root elongation have been combined into the root elongation inhibition (REI) as shown in the following equation:

$$REI(\%) = (1 - Ig) \times 100,$$

where Ig is the index of germination calculated according to the following equation:

$$Ig = \left(\frac{G_s \times L_s}{G_C \times L_C}\right),$$

where $G_n$ and $L_n$ are, respectively, the mean number of germinated seeds and root length in the sample solution and $G_c$ and $L_c$ are the mean values in the control.

2.4. Statistical Analysis. Data has been analyzed by ANOVA with post hoc Duncan’s multiple range test at $P \leq 0.05$ for mean values’ separation to highlight the effect of pyrolysis temperature of sewage sludge on chemical proprieties and phytotoxicity (STATISTICA 5.0, StatSoft Inc., Tulsa, USA). The differences between mean values have been annotated with alphabetical letters (a, b, c, . . .) where “a” is significantly different from “b” and “b” from “c.” Mean values annotated with the same letter are not statistically different. A Pearson product-moment correlation matrix ($P \leq 0.05$) is constructed to determine the strength of the relationship (r) between the measured parameters in each sample.

3. Results and Discussion

3.1. Effect of Pyrolysis Temperature on the Chemicals’ Recovery. The increase of pyrolysis temperature has a significant effect on the variation of physicochemical properties of the sewage sludge (Table 1).

With the increase of pyrolysis temperature, the content of volatile organic matter (VOM) in the produced biochars drops from 30.9 (260°C) to 14.2 (420°C) and 11% (610°C) compared to the raw SS (39.4%). Tomczyk et al. [62] explained that, at temperatures below 450°C, low-molecular-weight polymers are easily decomposed, while high-molecular-weight polymers are very resistant to thermal degradation. The decrease of volatile matters reflects the formation of recalcitrant compounds and the increase of stable carbon resistant to CO₂ volatilization [63]. In this regard, biochar carbon sequestration lasts longer; therefore, its production and land application may help mitigate climate change [64]. Moreover, the decomposition of labile organic matter, during pyrolysis, creates more pores [65] and increases the surface area of the biochars. The amendment of such biochars can help retain nutrients required for plant growth and prevent water runoff [66]. Substantial decreases are noticed for TN with the increase of temperature as follows: SS > PSS1 (260°C) > PSS2 (420°C) > PSS3 (610°C). For instance, TN decreases by 48.7, 67.6, and 89.2% after pyrolysis at 260, 420, and 610°C, respectively. Ye et al. [56] also reported the decrease of nitrogen in the biochar with the increase of pyrolysis temperature. The nitrogen element starts to volatilize at low temperatures (approximately 200°C) due to the cleavage and break of weak bonds within the biochar structure. Intani et al. [39] and Saffari et al. [67] showed that large amounts of N are lost as N₂O, NO, and NO₂. As pyrolysis temperature increases (above 300°C), the nitrogen is transformed into a heterocyclic aromatic form with more stable structures (i.e., pyridine, pyrrole, and quaternary nitrogen) [68]. In this regard, the land application of biochars produced at higher temperatures can reduce the volatilization of NH₃ [56], N₂O emissions [68], and nitrogen leaching [69]. The C/N ratio is generally used as a good indicator of the status of nutrients during mineralization [70]. It reflects the capacity of organic substrates to release inorganic N when incorporated into soils. The variation of C/ N depends on the total organic carbon (TOC) and total nitrogen (TN). According to this study, biochars have relatively lower levels of total nitrogen (TN). However, their very high TOC amount makes the C/N ratios fairly high (Table 1), indicating a net microbial immobilization. The significant decrease of C/N with the increase of pyrolytic temperatures from 260°C (PSS1) to 420°C (PSS2) and to 610°C (PSS3) is mainly attributed to organic C sequestration reflected by the loss of VOM (Table 1), as previously reported by Wei et al.
[71]. Accordingly, biochars with higher C/N (PSS1 and PSS2) may be useful as soil amendments by encouraging microbial immobilization [70] and slowing the mineralization rate [71].

Phosphorus (P) is the second most important nutrient after nitrogen for plant growth [42]. In this study, the available P follows the same trend as TN, showing lower concentrations in the biochars produced at 420 and 610°C (0.12 mg kg⁻¹) in comparison to the raw SS (0.014 mg kg⁻¹). Nevertheless, these concentrations are considered far below the range of desirable available P content (0.2 and 50 mg kg⁻¹) recommended for plant growth [72]. According to Novak et al. [73], P volatilization starts at 700°C, suggesting that available P in the biochars has changed to unavailable forms. This is consistent with the results of Qian and Jiang [74], reporting a significant reduction of P solubility in biochars compared to that in the raw material (SS).

Dai et al. [75] explained that, under the pyrolysis process, organic P is transformed into insoluble phosphate (e.g., FePO₄, AlPO₄, CaPO₄, and MgPO₄) [74–76], thus limiting the risk of P loss through runoff or leaching. As mineral P resources decrease, biochar can play an important role to recycle P from wastes like domestic sewage sludge [21, 77]. In the soil, P solubility is mainly regulated by the interaction of P with Ca²⁺, Mg²⁺, Al³⁺, and Fe²⁺/Fe³⁺ by forming Ca-Mg-Al or Fe-phosphates. Once the biochar is applied to acid soil, the pH of the soil increases, and the amount of adsorbed P decreases [78] and becomes more available. This was recently confirmed by Glaser and Lehr [77] showing that the addition of biochar can significantly increase the availability of phosphorus in agricultural soils by 460%.

In this study, the mineral content (MC) increases along with pyrolysis temperature, which highlights the highest percentages in the biochars produced at 420°C (PSS2: 85.5%) and 610°C (PSS3: 89%) (Table 1). The mineral content corresponds to the remaining noncombustible component referred to as ash [46, 47, 79]. Zielińska et al. [80] also showed that sewage sludge-derived biochars are characterized by high ash content (64.1–79.1%). According to Yang et al. [64], biochars, with high mineral content, have higher CEC. This can be attributed to the formation of O-containing surface functional groups including alkali salts, alkali trace metals, and polycyclic aromatic hydrocarbons (PAHs) [44, 63]. The greater the degree of formation of aromatic structures is, the higher the resistance of the biochar to microbial degradation will be [62]. The concentration of these nonpyrolyzed inorganic elements can increase the pH value of the biochar and affect soil chemistry (e.g., soil pH, nutrient availability, and metal toxicity) [81]. As expected, pH increases synchronically with pyrolysis temperature reaching 7.8 (at 420°C) and 9.11 (at 610°C) in comparison with the raw feedstock (6.74) (Table 1). However, at low pyrolysis temperature (260°C), pH decreases slightly but significantly in PSS1, showing the lowest pH among all the samples (6.35). Higher pH values in the biochars PSS2 and PSS3 are the result of the accumulation of alkali salts (i.e., Na, K, Ca, and Mg). In this study, both Na and K increase simultaneously with the increase of pyrolysis temperature. As such, K increases by 32, 46.38, and 46.36%, respectively, for PSS1, PSS2, and PSS3, and Na increases by 25, 34.7, and 35% respectively (Table 1). Therefore, Na and K show greater concentrations in the biochars (PSS2 and PSS3) with the highest pH (7.8 and 9.11, respectively), which confirms the interrelation between alkali salts and pH (r = 0.5 for Na; r = 0.65 for K) (Table 2).

Same observations were made by Yu et al. [82], explaining that, above 300°C, alkali salts begin to separate from the organic matrix and increase the pH of the product. The pH becomes constant at a temperature around 600°C while all the alkali salts are released from the pyrolytic structure [83]. Around 200–300°C, cellulose and hemicelluloses decompose and yield organic acids and phenolic substances that lower the pH of the products [82]. In addition to pH, EC also increase in the biochars (PSS2 and PSS3) produced at 420 and 610°C, reaching, respectively, 4.4 and 4.55 mS cm⁻¹ with respect to the control (3.09 mS cm⁻¹) (Table 1). Increases in EC are the result of the accumulation of chemical compounds responsible which determines the salinity increase (i.e., Na, K, Ca, and Mg) [78, 84]. This is justified by positive and significant correlations between EC and Na (r = 0.73) and K (r = 0.87) (Table 2). For alkaline soils (such as the majority of arid soils), it is important to select properly the raw materials and optimized pyrolysis temperature to produce the aimed biochars that prevent both soil salinization and sodicity. Overall, EC values are below the threshold required for plant growth, root development, and soil biological activity [85–87]. Nonetheless, biochar application on-field should be monitored particularly in arid soils characterized by dry spell which accentuates salt accumulation within the soil surface that leads to soil salinization [9, 11].

### 3.2. Effect of Pyrolysis Temperature on Trace Metal Concentration and Biochar Toxicity

The reuse of domestic sewage sludge has been proposed as a reliable and effective approach for soil fertility recovery because they enhance soil organic C storage [88] and enable valuable components to be recycled (e.g., N, P, and K) [89]. Nonetheless, sewage sludge can be highly contaminated with phytotoxic trace metals (i.e., Cr, Cd, Cu, Pb, and Zn) [12, 45] and pathogens [14] as well as toxic organic substances such as polyaromatic hydrocarbons, chlorobenzene, and plasticizers [38, 39]. Hence, they cannot be directly applied in farmland according to the EU legislation directives (EU) [14]. As confirmed by recent studies, one of the main characteristics of the pyrolysis process is the sanitization of the sludge’s pathogens and the destruction of organic compounds [14]. The presence of metals in the biochar is likely dependent on the origin of the feedstock or on pyrolysis conditions that may promote their accumulation in the biochar or their volatilization [44, 90, 91]. In this study, trace metals (Cu, Cd, Zn, Pb, and Cr), initially present in the raw SS, remain concentrated in the biochars (Figure 1).

As shown in Figure 1, the contents of trace metals in the sewage sludge vary significantly in the following order Zn > Cu > Cr > Pb > Cd, where Zn reaches 3 ppm whereas the content of Cd is only 0.027 ppm. The same trend was reported in the findings of Mancinelli et al. [91], as Zn is the
element with the highest concentrations followed by Cu, and Cd is the trace metal with the lowest concentrations in the feedstock and the biochars. Previously, Yuan et al. [21] explained that Cd tends to volatilize during pyrolysis and the other trace metals initially present in the feedstock generally remain and become concentrated in the biochar. Unexpectedly, trace metals (Zn, Cu, P, Cd, and Cr) concentrations in the biochars (PSS1, PSS2, and PSS3) are not significantly different from those in the raw feedstock (SS). The total concentration of Zn decreases significantly in the biochars PSS2 and PSS3 with the increase of pyrolysis temperature. On the other hand, Cu, Pb, and Cd concentrations decrease significantly in the biochars (PSS1 and PSS2) and increase in PSS3, with no significant variations compared to the raw feedstock (SS). As for Cr, the concentrations significantly decrease in PSS1 (260°C) and PSS3 (610°C) and increase in PSS2 (420°C). These results are different from the previous ones [61, 91, 92], which emphasize the increase of trace metals in the form of oxide and sulfide from 300 to 700°C. For instance, Méndez et al. [92] found that biochar derived from sewage sludge pyrolyzed at 500°C retains 31% of Cu, 30% of Pb, and about 28% of Ni, Cd, and Zn compared to the raw feedstock. Similarly, Lu et al. [61] found that biochars produced from sewage sludge pyrolyzed at 300, 400, 500, 600, and 700°C retain 90.4–98.3% of Pb, 96.4–99.5% of Zn, 92.5–99.3% of Ni, 85.8–98.5% of Cd, 81.5–94.5% of Cu, and 70.0–87.5% of Cr. This phenomenon was also observed in other studies during the pyrolysis of other feedstocks [18, 19, 25, 91], attributing trace metal retention to their low volatility [84]. Overall, total concentration of the five trace metals in the biochars (PSS1, PSS2, and PSS3) remains below the regulatory limits set by the European Biochar Certificate [93]. Accordingly, the following maximum values for heavy metals correspond to 40 ppm for Zn, 12 ppm for Pb, 10 ppm for Cu, 8 ppm for Cr, 3 ppm for Ni, and 0.1 ppm for Cd. This could be attributed to the low concentrations of trace metals detected in the domestic sewage sludge (SS) (Figure 1).

The effect of pyrolysis temperature on the concentration of trace metals in the biochars was the main focus of research on the production and characterization of biochars [11]. However, the toxicity of the produced biochar is still unclear [41]. In this study, a phytotoxicity test is used as an effective and a low-cost equipment to identify the toxic effects of the produced biochars on root elongation inhibition (REI) of lettuce seeds (Figure 2).

Sewage sludge pyrolysis has a significant effect (P ≤ 0.05) on the lettuce growth, showing lower REI in the biochars (PSS1, PSS2, and PSS3) compared to the raw feedstock (SS) (Figure 2). The lowest REI is found in the biochars (PSS1 and PSS2) produced at low temperatures (260 and 420°C, respectively). This implies that PSS1 and PSS2 do not cause root elongation inhibition of lettuce.
Figure 1: Variation of trace metal (Cu, Cd, Zn, Pb, and Cr) concentrations in the biochars produced at 260°C (PSS1), 420°C (PSS2), and 610°C (PSS3) with respect to the raw sewage sludge (SS). For each parameter, sample mean values with the same letters are not statistically different at $P \leq 0.05$.

Figure 2: Variation of root elongation inhibition of lettuce seeds in the biochars produced at 260°C (PSS1), 420°C (PSS2), and 610°C (PSS3) with respect to the raw sewage sludge (SS). For each parameter, sample mean values with the same letters are not statistically different at $P \leq 0.05$. 
produced at higher temperature (420 and 610°C) and sub-
content (MC) particularly in the biochars (PSS2 and PSS3)
formation of the organic elements (C, N, and P) into mineral
properties (e.g., pH, EC, VOM, Na, and K) and the trans-
 elongation inhibition using lettuce seeds. Pyrolysis tem-
toxicity of the produced biochars is investigated through
(TOC, TN) and the nutrient status (P, K, and MC). (+æhe
sewage sludge is studied by the macronutrient content
material. (+æhe agronomic potential of biochars derived from
sludge pyrolysis at 420°C (for 40 minutes) is recommended
inhibition compared to the other samples. All in all, sewage
(PSS2) has a minimum contribution to the root elongation
compared to PSS3 and SS. (+æhis is in line with the findings
regions. Further studies should investigate the formation of
radicals’ formation under SS pyrolysis and their contribution to biochar toxicity.

4. Conclusion
In this study, sewage sludge is pyrolyzed at ascended tem-
peratures (260, 420, and 610°C) and compared to the raw
material. The agronomic potential of biochars derived from
sewage sludge is studied by the macronutrient content
(TOC, TN) and the nutrient status (P, K, and MC). The
toxicity of the produced biochars is investigated through
total concentrations of trace metals and the index of root
elongation inhibition using lettuce seeds. Pyrolysis tem-
perature has a strong influence on biochar’s physicochemical
properties (e.g., pH, EC, VOM, Na, and K) and the trans-
formation of the organic elements (C, N, and P) into mineral
stable forms. This is proved by the increase of mineral
content (MC) particularly in the biochars (PSS2 and PSS3)
produced at higher temperature (420 and 610°C) and sub-
sequently the increase of biochar’s pH and EC. Unexpect-
edly, biochars have generally lower trace metal
concentrations compared to the raw feedstock, especially in
the biochar produced at 420°C (PSS2). Hence, biochar
(PSS2) has a minimum contribution to the root elongation
inhibition compared to the other samples. All in all, sewage
sludge pyrolysis at 420°C (for 40 minutes) is recommended
for reuse as a safe soil amendment in arid and semiarid
regions. Further studies should investigate the formation of
free radicals and confirm their contribution to the biochar
toxicity.

Data Availability
All data used to support the findings of this study are in-
cluded in the article and will be, in case the article will be
accepted, accessible to readers.

Conflicts of Interest
The authors declare no conflicts of interest.

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