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Research article

# Impact of temperature and residence time on sewage sludge pyrolysis for combined carbon sequestration and energy production

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ABSTRACT

Environmental challenges related to sewage sludge call for urgent sustainable management of this resource. Sludge pyrolysis might be considered as a sustainable technology and is anticipated to support measures for mitigating climate change through carbon sequestration. The end products of the process have various applications, including the agricultural utilization of biochar, as well as the energy exploitation of bio-oil and syngas. In this research, sewage sludge was pyrolyzed at 500 °C, 600 °C, 750 °C, and 850 °C. At each temperature, pyrolysis was explored at 1hr, 2hrs, and 3hrs residence times. The ratio $(H/C_{org})^{at}$ was tapped to imply organic carbon stability and carbon sequestration potential. Optimum operating conditions were achieved at 750 °C and 2hrs residence time. Produced biochar had $(H/C_{org})^{at}$ ratio of 0.54, while nutrients' contents based on dry weight were 3.99%, 3.2%, and 0.6% for total nitrogen (TN), total phosphorus (TP), and total potassium (TK), respectively. Electrical conductivity of biochar was lesser than the feed sludge. Heavy metals in biochar aligned with the recommended values of the International Biochar Initiative. Heat content of condensable and non-condensable volatiles was sufficient to maintain the temperature of the furnace provided that PYREG process is considered. However, additional energy source is demanded for sludge drying.

## 1. Introduction

Global annual sewage sludge generation is mounting at a very high rate due to the rapid urbanization and industrialization with an estimated quantity of 45 million dry tons of sludge in the year 2017 [1]. Sludge treatment costs range between 160 and 310 Euro/t in Europe, which might correspond to 40–60% of the total cost associated with managing the entire wastewater treatment plant [2]. Accordingly, research was directed for more feasible sludge management alternatives. Jordan is not an exception and is faced with enormous challenges related to sewage sludge management. Presently, the generated sludge is disposed of through either landfilling or accumulation in designated areas within wastewater treatment plants. In instances where on-site storage is unavailable, sludge is

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transported to designated dumping sites. As a result, operators of these plants encounter various environmental and managerial challenges, such as the recent additional restrictions enforced on sanitary landfilling of sludge, leaching of pollutants into groundwater and water bodies during the rainy season, and air pollution. Challenges will be aggravated in the future with increasing sludge quantities, which are projected to range between 132 and 158 Kilotons (dry matter) in 2035 [3]. Existing regulations do not promote sludge valorization mainly due to social constraints. The Jordanian cabinet commenced a national discourse since 2016 in order to coordinate efforts calling for the safe use of sludge and to improve social acceptability of valorization options with hardly any progress in this regard.

Thermal treatment of sewage sludge is gaining more attention especially in urbanized areas dealing with space and odors constraints. A well-established thermal treatment process is incineration in which energy is recovered as electricity and heat. Additionally, incineration might be a favorable option when considering treatment costs [4]. However, challenges arise with gas cleaning, notably related to chlorine corrosion and the formation of dioxins and furans [5,6]. Other thermal treatment options include gasification and pyrolysis. While, gasification faces technical immaturity [6], pyrolysis might be advantageous due to the product market value and flexibility when small-scale systems are considered [4]. This process not only combines net carbon removal from the atmosphere [7], but also produces socially accepted biochar. Pyrolysis is defined as the thermal decomposition of organic matter at high temperatures under oxygen-deficit conditions [8]. It is considered one of the most economic and effective methods to sequester carbon in the environment and assist climate change mitigation strategies. This is mainly due to the fact that produced biochar is enriched with stable carbon that can stay in soil over 100 years [9] -$BC_{+100}$- and up to 1000 years [10]. For instance, it was estimated that pyrolizers used to process biomass in the USA might decrease carbon emissions by 10%, simultaneously replacing 25% of the country's demand for fossil fuel [11]. Stability of carbon in soil is specified by the molar ratio of $(H/C_{org})^{at}$ owing to the clear correlation between $(H/C_{org})^{at}$ ratios and $BC_{+100}$ [12]. In addition to carbon sequestration potential, generated biochar has likely commercial applications such as utilization as adsorbent [13,14], soil amendment [15], soil remediation to increase fertility, heavy metals immobilization, and acidity neutralization [16]. Pyrolysis process also produces bio-oil and syngas, which can be utilized as energy source. Moreover, the technology allows for efficient sewage sludge hygienization [17] and substantial volume reduction [18]. The main operating conditions that affect pyrolysis process are temperature, residence time and heating rate [19]. Temperature is considered as a central process parameter [20] and can be subdivided into low temperature processes ranging between 500 and 600 °C, intermediate temperatures ranging between 600 and 800 °C [21], and high temperature processes of up to 900 °C [22]. Residence times diverge between few seconds up to several hours, while heating rates range from few degrees per minute up to 650 °C/min [19]. Other factors influencing the process include feedstock particle size with tinier particle size known to improve cracking process with less $CO_2$ gas production [23]. Comprehending the correlation between operation conditions and pyrolysis products distribution is vital for a successful implementation of the technology [23]. Moreover, the impact of operation conditions on the quality of biochar is central to promote the technology particularly with respect to further potential agricultural applications.

In slow pyrolysis of sewage sludge, literature is still not conclusive regarding the impact of temperature and residence time on biochar quality particularly with respect to carbon stabilization $(H/C_{org})^{at}$. The $(H/C_{org})^{at}$ value recommended by the International Biochar Initiative (IBI) is set at values below 0.7, which can be obtained at temperatures $\geq$ 500 °C based on data collected from literature [14,24–29]. However, $(H/C_{org})^{at}$ were also attained at lower temperatures of 300–400 °C [30,31] and at a temperature range of 600–650 °C [32–34]. Residence times were not often reported, but were found to have an effect on carbon stabilization and biochar yield. For instance, Wang et al. [35] revealed that increasing retention time from 1hr to 2.5hrs resulted in biochar yield decline from 52% to 45%. Moreover, very few mathematical models are proposed to describe sewage sludge pyrolysis process due to complexity and variability of sludge characteristics [36]. Hence, further research is required to explore the influence of various parameters on sludge pyrolysis before it can be effectively modeled. A project funded by the German Development Cooperation (GIZ) on sustainable sludge management in Jordan is planning to introduce a pyrolysis plant in the south of Jordan and were requesting support regarding the optimum operating conditions, principally those related to temperature and residence time. Consequently, the main objective of this research is to explore the impact of temperature and residence time on the products' distribution during sewage sludge pyrolysis in addition to assessing biochar quality particularly with respect to agricultural and soil applications. Moreover, energy recovery potential of sewage sludge pyrolysis is explored for the sustainable operation of the system.

## 2. Materials and methods

### 2.1. Sludge source and experimental setup

Sewage sludge was collected from Wadi Musa wastewater treatment plant (WM-WWTP) placed at the south of Jordan with

**Table 1**
Proximate and Ultimate analysis of feed sludge.

| Proximate analysis | | | Ultimate analysis | | | | | | HHV |
|---|---|---|---|---|---|---|---|---|---|
| **Moisture (%)** | Volatile matter (%) | Ash content (%) | C (%) | H (%) | N (%) | S(%) | O[a] (%) | $(H/C_{org})^{at}$[b] | (MJ/kg) |
| **5.0** | 60 | 35 | 36 | 5.4 | 7.0 | 1.8 | 15.8 | 1.8 | 15.6 |

[a] Calculated by subtraction.
[b] $(H/C_{org})^{at}$ is the molar ratio.

coordinates of 30.3184450, 35.4707790 according to the World Geodetic System WGS84. The choice of this plant was made because it represented a viable location for the installation of a pyrolysis unit according to the GIZ and the Jordan Ministry of Water and Irrigation (personal communications). The plant is based on extended aeration system, representing 80% of the existing wastewater treatment systems in Jordan. Sludge was collected from the drying beds and had a water content of 50% according to data provided by the operator. Sludge was collected from the top layers of the drying beds in order to avoid mixing with the bottom sand layer. Sludge was oven dried at 105 °C for 24 h, grinded by means of jaw crusher and sieved for sizes less than 2 mm. Ultimate and Proximate analyses of dried sludge are shown in Table 1. For each pyrolysis run, a total weight of 1.5 kg of feed sludge was manually introduced into a stainless-steel tubular packed-bed reactor centered in a tubular vertical furnace as shown in Fig. 1. The reactor has a total length of 181 cm and a diameter of 10 cm. Reactor's temperature was controlled by Proportional-Integral-Derivative (PID) controller. A thermocouple was installed at the center of the reactor in order to check temperature that was ramping 10° per minute until it reached the set temperature. Sludge was then kept at a selected temperature for a certain residence time. Reactor was operated in batch mode at 500 °C, 600 °C, 750 °C, and 850 °C. For each temperature, three residence times were investigated, namely, 1hrs.

2hrs, and 3hrs. Before each run, sludge was loaded into the reactor and $N_2$ gas was utilized to flush the reactor for around 10 min. Nitrogen gas was then kept for the whole experimental run at a flow rate of 200 ml/min. Volatile products were condensed to separate the bio-oil (as show in Fig. 1) and the non-condensable gases were passed through activated carbon column before final release into the atmosphere. Yields of both biochar and bio-oil were measured after cooling to room temperature. Mass balance was used to calculate gas yield. For the operational condition that generated the best biochar quality with respect to $(H/C_{org})^{at}$ ratio, samples were further analyzed in duplicates for heavy metals and chemical composition and were assessed according to IBI recommended values.

### 2.2. Chemical analysis

Samples used for biochar and sludge quality analysis were further grinded by roller mill to obtain a powder texture with size passing mesh # 200. Moisture content, total solids (TS), and volatile solids (VS) were analyzed following ASTM [37]. Total ash was analyzed using standard method [27]. Heat of combustion for bio-oil and biochar were determined following ASTM [38]. Inorganic carbon was measured and revealed a minor contribution to the total carbon. Accordingly, organic carbon was assumed to equal total carbon. Electrical conductivity (EC) and pH were determined according to the method described earlier [39]. Total C, H and N (ultimate analysis) were determined using dry combustion elemental analyzer EA3000 Euro Vector-Italy. Liming potential as %$CaCO_3$ equivalent was determined according to method described earlier [40]. Heavy metals were determined according to Radojevic and Bashkin [41]. All test analyses were executed in duplicates.

### 2.3. Calculations

A. Thermal calculations

Regarding energy required for sludge drying, the following equations were used [42].

### 2.4. Energy required for sludge heating to 100 °C

$$Q_s = M_2(T_2 - T_1)[(1 - R_2)C_s + R_2C_i] \tag{1}$$

$$M_2 = M_1(1 - R_1) / (1 - R_2) \tag{2}$$

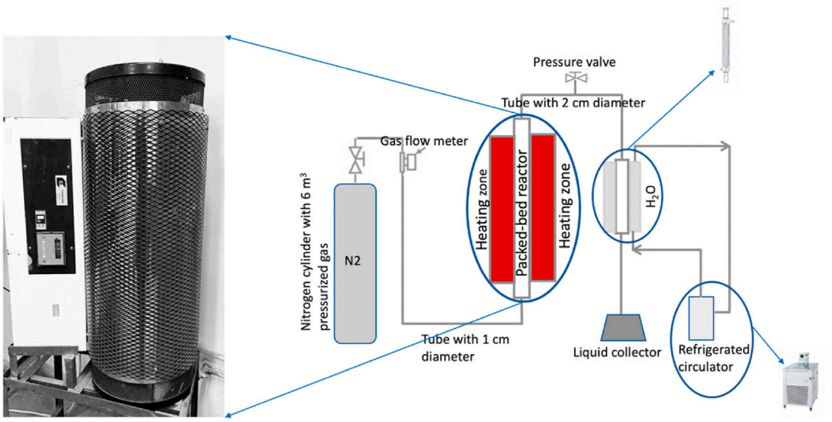


**Fig. 1.** Laboratory pyrolysis set up used in this study.

Where $Q_s$ is the heat required for sludge drying (kJ), $M_2$ is the sludge mass at a certain moisture content after drying (kg), $T_1$ and $T_2$ are sludge temperatures before and after drying ($^oC$). $R_2$ is the moisture content of dried sludge (%), $C_s$ is the specific heat of sewage sludge (kJ/(kg*$^o$C)) and was assumed to be 1.244 kJ/(kg*$^o$C) [42], $C_i$ is the specific heat of water (kJ/(kg*$^o$C)) at 13 °C (average water temperature during winter at storage location), $M_1$ is the sludge mass at a certain moisture content before drying (kg), $R_1$ is the sludge moisture content before drying (%).

### 2.5. Energy required for water evaporation

$$Q_w = W[r_i + (T_2 - T_1)C_i] \tag{3}$$

$$W = M_2(1 - R_2) / (x_1 - x_2) \tag{4}$$

$$x = R/(1 - R) \tag{5}$$

Where $Q_w$ is the heat needed for water evaporation (kJ), W is evaporation water in (kg), $r_i$ is the latent heat of vaporization of water (kJ/kg) and equals to 2260 kJ/kg, $x_1$ and $x_2$ are moisture content before and after drying.

### 2.6. Total energy required for thermal drying

$$Q_{req} = Q_s + Q_w + Q_L \tag{6}$$

Where $Q_{req}$ is the heat to be provided by the drying system, $Q_L$ is the heat loss during drying (kJ) and might be calculated using the following equation:

$$Q_L = \alpha(Q_s + Q_w) \tag{7}$$

Where $\alpha$ is heat loss coefficient and was assumed to be 10% [43]

### 2.7. Energy required for sludge pyrolysis

$$Q_f = C_s \times M_s \times \Delta T \tag{8}$$

Where $Q_f$ is the energy required for the furnace (kJ), $C_s$ is the specific heat of sewage sludge (kJ/kg*$^o$C) and was assumed to be 1.244 kJ/(kg*$^o$C) [42], $M_s$ is the sludge mass (kg), $\Delta T$ is the difference in temperature.

### 2.8. Heat of combustion

$$Q = (tE - e_1 - e_2 - e_3 - e_4) / 1000g \tag{9}$$

Where $Q$ is the heat of combustion at constant volume expressed as MJ/kg (after sample centrifuge), $t$ is the corrected temperature rise ($^o$C), E is the energy equivalent of calorimeter (MJ/$^o$C), $e_1$, $e_2$, $e_3$, and $e_4$ are corrections described in ASTM [38], $g$ is the weight of the sample (g).

B. Mass reduction on heavy metals

$$\%\ reduction\ of\ heavy\ metal\ mass = \frac{(W_1 \times C_1) - (W_2 \times C_2)}{W_1 \times C_1} \times 100 \tag{10}$$

Where $W_1$ is the wight of feed sludge (g); $C_1$ is the concentration of the heavy metal in the feed sludge sample (mg/g); $W_2$ is the weight of the biochar sample (g); and $C_2$ is the concentration of the heavy metal in biochar sample (mg/g).

### 2.9. Statistical analysis

STATA8 software was used to conduct a multiple regression analysis in which the significant impact of temperature and residence time (independent variables) on elemental composition (Cwt%, Hwt% and Nwt%) were tested at a 0.05 level of significance.

## 3. Results and discussion

### 3.1. Sewage sludge biochar and bio-oil yields

Fig. 2a illustrates the biochar yields achieved at various operating temperatures and residence times. As anticipated, there was a decline in biochar yields with rising temperatures, transitioning from 59% at 500 °C to 48% at 850 °C. Hossain et al. reported a decrease in biochar yield from 57.9% to 52.4% when sludge pyrolysis temperature increased from 500 °C to 700 °C [24], while others reported biochar yield of 44–45% at pyrolysis temperature of 700–800 °C [19,44,45]. The influence of residence time on biochar yield is noticeably less pronounced, as depicted in Fig. 2a. This observation aligns with findings from other researchers' studies [25,46] though shorter residence times were investigated. Several factors were reported to affect pyrolysis yield and yield distribution including pyrolysis temperature, gas residence time, feeding rate, feed particle size, reaction atmosphere composition, sewage sludge composition, and use of catalyst [47]. The diverse and intricate makeup of sewage sludge often results in a wide range of yields and characteristics when undergoing pyrolysis process [48]. The main polymeric constituents of activated sludge comprise proteins, carbohydrates and lipids. Decomposition temperatures for lipids, proteins and carbohydrates were shown to be 200–635 °C, 209–800 °C and 164–497 °C, respectively [49–51], which are within the temperature range applied in this research. Additional components within the sludge include celluloses, hemicelluloses, and lignin, which have been documented to undergo thermal decomposition within the temperature range of 450–600 °C [52]. Furthermore, moisture-related mass loss was noted to occur at temperatures up to 217 °C [53], whereas temperatures exceeding 600 °C were linked to secondary decomposition of inorganic substances [54] and some organic matter -as will be discussed in the following section-. The slightly higher biochar yield at 850 °C might be indicative of gas condensation within the reactor and probably repolymerization at prolonged residence times of 2 and 3 h. In general, gas condensation might occur mainly at longer vapor residence time during fast pyrolysis in which both syngas and biochar formation were enhanced and bio-oil yield was minimized [14]. Nevertheless, there is a lack of relevant literature addressing the process under conditions of extended residence times and elevated temperatures during slow pyrolysis of sewage sludge.

The bio-oil yield exhibited a decreasing trend as the temperature was elevated from 500 to 850 °C for residence times of 2 and 3 h, as depicted in Fig. 2b. However, at a residence time of 1 h, the bio-oil yield initially decreased with a temperature rise from 500 to 600 °C, and subsequently demonstrated a nearly stable pattern as the temperature climbed from 600 to 850 °C. Two observations can be stated based on these results: firstly, and considering mass balance, longer residence times apparently promoted the formation of gaseous products while minimizing bio-oil production. Prior studies have also noted a decline in bio-oil yield beyond 600 °C, accompanied by an increase in syngas production [29,55]. In sewage sludge pyrolysis, some researchers have reported a peak bio-oil yield of 28.6% at 500 °C [56] after which the yield declined. Maximal oil production during pyrolysis has been highlighted within the temperature range of 450–575 °C in other investigations [47,57–59]. Consistent with this, certain researchers have observed negligible alterations in bio-oil yield at temperatures exceeding 500 °C, aligning with the findings of this study at a 1-h residence time [53]. The decrease in bio-oil yield at higher temperatures and residence times might be attributed to a reduction in the formation of condensable

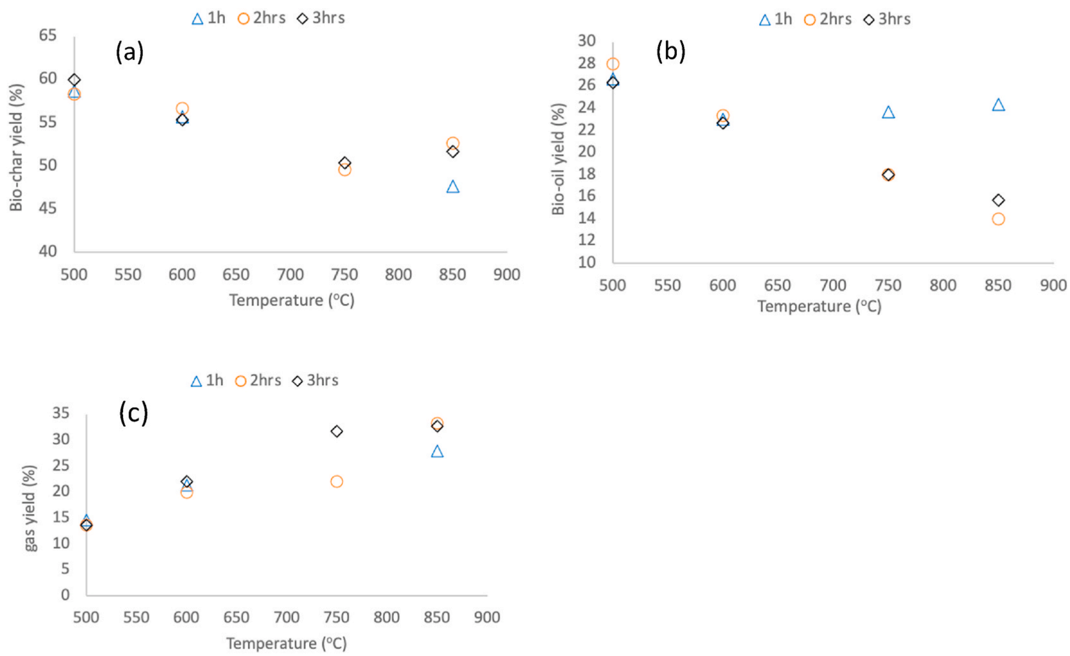


**Fig. 2.** Sludge pyrolysis biochar and bio-oil yields as a function of temperature and residence time. (a) Bio-char yield, (b) bio-oil yield, (c) gas yield calculated on mass balance basis.

volatile products [59] and secondary cracking of oil molecules noticed at temperatures over 650 °C leading to higher bio-gas yield [60].

Finally, the increase in temperature leads to higher gas yield and a decrease in biochar yield as shown in Fig. 2c. At 500 °C and 600 °C, residence time has minimal impact, but at 750 °C, there's a significant effect, showing 22 wt% and 32 wt% gas production at 2hrs and 3hrs, respectively. At 850 °C, increasing residence time from 2hrs to 3hrs has minimal impact, while an increase from 1hr to 2hrs results in gas yield values of 28 wt% and 33 wt%, respectively. Similar findings were reported by other researchers at high temperatures of 850 °C, achieving a gas yield of 34 wt% within residence times ranging from 1 to 2 h [61]. The produced syngas is primarily composed of $CO_2$, CO, $H_2$, and $CH_4$, making up to 90 vol%, with the remaining consisting of hydrocarbons, nitrogen, and other minor products [62]. As temperature increases, there is a tendency to decrease the $CO_2$ and to increase $H_2$ (% vol) [63] indicating that temperature has a main role in syngas composition.

For practical applications of this research, condensation process will not be required since both condensable and non-condensable volatiles (bio-oil and syngas) will be combusted in an integrated combustion chamber to obtain an energy self-sustained system [43]. For instance, PYREG process can be used for full-scale application at WM-WWTP. The process utilizes a twin-screw reactor for sludge pyrolysis at 500–800 °C. There are currently two full scale PYREG sewage sludge treatment plants in Germany in which produced biochar can be directly used as fertilizer [6]. Combustion of generated volatiles takes place in a combustion chamber by means of flameless oxidation (FLOX burner) with minimal production of nitrogen oxides [6]. Exhaust gas of the burner is used to heat the pyrolyzer, and the gas is subsequently cleaned by wet scrubbing and activated carbon filters [6]. It should be noted that emissions of CO, $CH_4$ and other products of incomplete combustion in this process are almost one order of magnitude less than simple pyrolysis technologies like the Flame Curtain Kiln, and additional reduction on the emissions can be controlled by air to fuel ratio [64]. Moreover, volatiles combustion using PYREG process strongly reduces the aerosol emissions with reported values of 0.05–2.5 g/kg [65]. In general, it was shown that sludge pyrolysis did not lead to higher emissions as compared to a reference carbon-based material [63]. Management of spent activated carbon should be taken into consideration in full-scale applications in order to minimize any anticipated negative environmental impacts.

### 3.2. *Ultimate analysis of biochar*

The multiple regression analysis run to predict the significance of temperature and residence time on the elemental composition of sewage sludge biochar showed that temperature had a significant impact on the elemental composition as shown in Table 2. From the table, we can see that a one unit increase in temperature is associated with a 0.024 percentage point decrease in carbon, holding all other variables constant. Moreover, a one unit increase in temperature is associated with a 0.005 percentage point decrease in hydrogen, and a 0.012 percentage point decrease in nitrogen, holding all other variables constant. This is statistically significant considering the p-value is smaller than 0.05. For the purpose of this analysis, it was assumed that the sludge is homogeneous with respect to composition. Moreover, it was assumed that the average particle size of feed sludge, heat distribution and sweeping gas distribution in all runs were constant.

Biochar main elemental composition and the $(H/C_{org})^{at}$ ratio for each operational condition are shown in Fig. 3. The maximum reduction on carbon content was obtained at 850 °C (2 and 3hrs residence time) accounting for 34 wt% as shown in Fig. 3a. Carbon content of biochar produced at 1hr residence time and 850 °C was 33.7 wt%, which is higher than that of biochar produced at 2 and 3hrs accounting for 23.9 and 23.7 wt%, respectively. The highest reduction rate on carbon content occurred at a temperature higher than 750 °C and can be attributed to the decomposition of inorganic carbon, which is originating mainly from calcium carbonate [66]. Thermal decomposition of $CaCO_3$ was noticed at temperatures higher than 650 °C [67]. Moreover, increased devolatilization of solid hydrocarbons and steam partial gasification of the carbonaceous residue might also be possible at elevated temperatures [68]. Apparently, longer residence times at elevated temperatures improved secondary reactions which is also evidenced by the lower oil yields (Fig. 2b) and increased gas yields (mass balance). Hydrogen was reduced by 34 wt% when sludge was pyrolyzed at 500 °C with no significant difference found for different residence times at alpha level of 0.05 as depicted in Fig. 3b. Further reduction on hydrogen was observed with increasing temperature up to 850 °C. Three types of reactions might be responsible for hydrogen reduction in biochar at this high temperature, namely, secondary decomposition of organic matter, dehydrogenation of organic fragments, and endothermic reactions like steam gasification of carbon [69]. It was reported that high temperatures of around 900 °C and long residence time contribute to generation of more gaseous products [69] including hydrogen that can represent up to 37% of the gaseous components and is generated through steam gasification reaction catalyzed by metals present in the sludge [70]. In general, the major reactions taking place below 500 °C are dehydration, decarboxylation and decarbonylation, while dehydrogenation is the main reaction taking place at high temperatures [23], which is in agreement with the obtained results in this research. Along with this decreasing trend of hydrogen and carbon, $(H/C_{org})^{at}$ also decreased from 1.2 to 0.57 when temperature increased from 500 °C to 850

**Table 2**
Multiple regression analysis showing the significance of temperature and residence time on elemental composition.

| | %C | | %H | | %N | |
|---|---|---|---|---|---|---|
| | **β** | ***P*-value** | **β** | ***P*-value** | **β** | ***P*-value** |
| Residence time | −1.212 | 0.340 | −0.093 | 0.760 | −0.416 | 0.296 |
| Temperature | −0.024 | 0.010 | −0.005 | 0.027 | −0.012 | 0.001 |

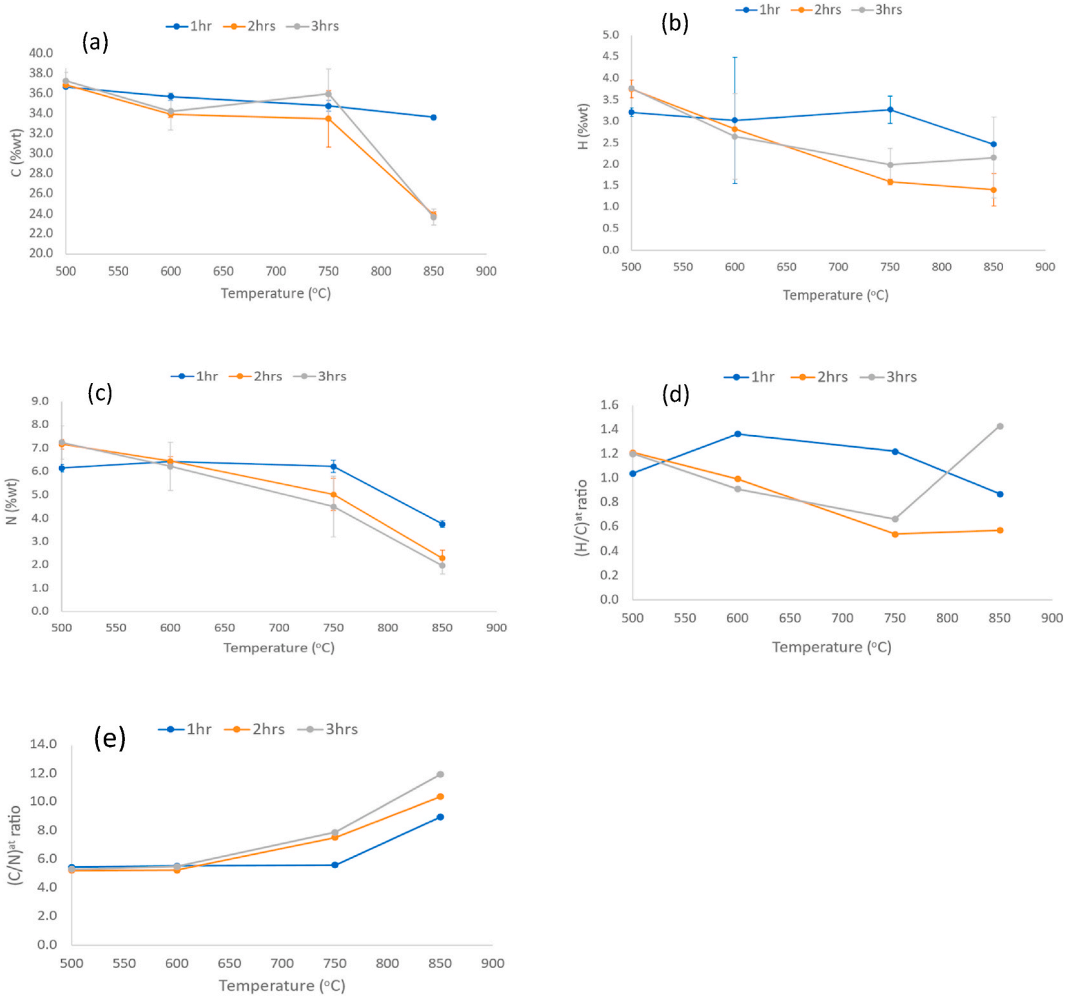


**Fig. 3.** Elemental composition of biochar at different temperatures and residence times. (a) C (%wt), (b) H (%wt), (c) N (%wt), (d) ratio of $(H/C)^{at}$, (e) ratio of $(C/N)^{at}$.

°C, which is indicative of progressive carbonization occurring with increasing temperature and higher aromaticity obtained at higher temperatures [44]. Higher aromaticity implies resistance to decomposition and longer and stable retention in soils [71]. The IBI recommended a maximum $(H/C_{org})^{at}$ value of 0.7 for the final product. $(H/C_{org})^{at}$ increased at 850 °C and prolonged residence time of 3 h, which was difficult to explain based on the existing literature.

In line with the IBI recommendations, a temperature of 750 °C and a residence time of 2 h are deemed adequate for generating environmentally stable carbon. This is evident from the production of biochar with an $(H/C_{org})^{at}$ value of 0.54 as shown in Fig. 3d, which is nearly identical to that produced at 850 °C under the same residence time.

Biochar nitrogen content -as depicted in Fig. 3c-was reduced by increasing the temperature with residence time impact noticed only at temperatures higher than 750 °C. At a temperature of 750 °C, biochar still contains about 5-6 wt% nitrogen. Other researchers indicated that nitrogen conversion was promoted within a temperature range of 600–800 °C, while it was inhibited by mineral content of sewage sludge at lower temperatures [51]. Biochar N content decreased to 1.9 and 3.7 at a temperature of 850 °C depending on residence time. Biochar N content was also reported to significantly decrease when temperature was further increased from 800 °C up to 1000 °C [72]. As well, the increase in $(C/N)^{at}$ ratio (Fig. 3e) of biochar with increasing temperature is indicative of the reduction of N-related functional groups on the surface of biochar [73]. The $(C/N)^{at}$ ratio of the sludge was 5.1 for original feedstock and increased from 5.2 to 5.5 to 9.0–12.0 when temperature was increased from 500 °C to 850 °C suggesting a lower nitrogen leaching capacity when biochar is incorporated into the soil [73]. In general, nitrogen present in sludge in the form of proteins, pyridine, pyrrole-N, and nitrogen oxides [51]. Inorganic N content of the sludge was reported to reduce to zero at a temperature range of 300–500 °C [74], while pyridine-N and pyrrole-N content is reduced at temperature range between 500 and 800 °C [51]. As for proteins (representing around 90% of N [74]), a proposed transformation pathway was suggested in which proteins in sewage sludge are first decomposed to amine-N and nitrile-N at a temperature range of 300–550 °C and then amine-N is further transferred to heterocyclic-N with simultaneous release of $NH_3$, while nitrile-N is further transferred to HNCO [75]. At temperatures higher than 550 °C, heterocyclic-N is decomposed and HCN is released [75]. $NH_3$ and HCN are $NO_x$ and $N_2O$ precursors and might be considered as a limitation in sewage sludge pyrolysis [76,77]. Ren et al., concluded that yields of HCN and $NH_3$ are affected by concentrations of cellulose, hemicellulose and lignin [78], while other factors affecting transformation of nitrogen content in sewage sludge into gases during pyrolysis include the applied atmosphere (Ar, $CO_2$, $N_2$, etc.), mineral matter content, and heating rate [79]. Control of HCN and $NH_3$ must be considered in sewage sludge pyrolysis in order to minimize environmental and health impacts [79,80].

## *3.3. Characterization of biochar generated at 750 °C and 2 h residence time*

### *3.3.1. Proximate analysis and calorific content*

Proximate analysis and calorific content are shown in Table 3. Moisture content of the biochar was 1.9 wt% and the volatile matter content declined as expected from 60 wt% for the feedstock to 36 wt% after pyrolysis. Reduction on volatile matter content was noticed by other researchers; for instance, Hossain et al. reported a volatile matter reduction from 50.2 wt% for raw digested sewage sludge to 15.8 wt% for biochar after pyrolysis at 700 °C [24], while others reported a reduction from 50 wt% to 20 wt% for biochar pyrolyzed at 600 °C [81]. Volatile solids were also reduced from 50.9 wt% for sewage sludge to 8.95 wt% for resulting biochar [53]. Volatile solids reduction is basically due to thermal decomposition and results in the formation of aromatic structure of residual organic matter. Discrepancies observed in literature in volatile solids destruction of sewage sludge are probably due to different pyrolysis conditions including reactor's type (e.g., fixed bed, fluidized bed, etc.), furnace alignment (horizontal versus vertical), sweeping inert gas flow rate, gas type, and heat transfer conditions. For example, increasing sweeping gas flow rate might cause a rapid removal of volatiles from reaction medium resulting in reduced secondary reactions [82], which ultimately will affect char volatile matter content. Moreover, heat transfer is affected by solid particle shrinkage and, consequently, higher heat transfer is attained towards the interior of the solids reducing the residence time of volatiles within the solid particle [83]. Ash content of biochar was 55 wt%, which is slightly lower compared with values reported by other researchers and range 60–83 wt% [84,85]. The ash content is a function of the feedstock composition and the rise in ash content commonly described for biochar is a typical result of the pyrolysis process due to loss of organic matter and accordingly, the concentration of minerals in the final biochar product [31].

The biochar that was generated exhibited a HHV of 12.73 MJ/kg, a measurement that aligns with findings presented by other researchers who investigated biochar originating from sewage sludge [19,32,44,86,87]. The decreased energy content in the biochar compared to the feed sludge is attributed to the creation of volatile compounds, both condensable and non-condensable, which carry the remaining energy initially present in the feed sludge. Consequently, there's also a potential for the utilization of this biochar as a solid fuel within power plants or via amalgamation with coal [53]. It is important to note that the calorific value of biochar depends on factors like carbon content and the source of the sludge (digested or non-digested), typically ranging between 8.5 and 17 MJ/kg [45]. Nonetheless, if the intended purpose involves energy applications, opting for dried sludge (e.g., solids content higher than 85 wt%), rather than biochar, would be a more reasonable choice due to its higher energy content that ranges between 8 and 21 MJ/kg [88]. In terms of the produced bio-oil, its calorific value was determined to be 32.7 MJ/kg, a figure that is in agreement with values found in the existing literature [14,62,89]. In slow pyrolysis, bio-oil and syngas can be used to cover energy requirements of sewage sludge pyrolysis with calculated energy efficiency (energy output/energy input ratio) ranging 87–100% depending on the moisture content of the feed sludge [90–92], though research is still required to obtain energy efficient preprocessing sludge drying techniques [92].

### *3.3.2. pH, liming potential, and electrical conductivity*

The pyrolysis process led to a rise in pH from 6.47 in the initial feedstock to 8.33 in the resulting biochar. This pH elevation following pyrolysis is a commonly observed phenomenon [73,85,93] and could stem from mechanisms such as polymerization, condensation reactions, and the loss of acidic groups [46]. Additionally, this pH increase might be attributed to the augmentation of inorganic constituents, resulting from the separation of alkali metal salts from the organic matrix due to higher temperatures [27]. Furthermore, the presence of pyridine-like compounds resulting from amine functional groups could potentially contribute to the observed pH rise [44]. The biochar exhibited a liming potential of 26% as $CaCO_3$, in contrast to the 12.5% measured for the raw sludge samples. This liming potential is notably high when compared to certain biochar sources, while it aligns with liming potential of biochar derived from paper mill waste and tomato green waste, demonstrating comparable characteristics [94,95]. Increased liming potential might be attributed to the high mineral concentration of sludge specifically to the calcium and potassium carbonates and accordingly liming potential is generally controlled by biochar ash content and chemical composition [96]. Worth noting is that biochar liming potential gives additional value when utilized as a soil conditioner for acidic soil. However, it was noticed that pH of biochar decreases to original soil pH with aging, which implies that biochar liming potential is limited after application to soil [97]. Some researchers have noted that the liming potential has the advantage of significantly decreasing Mn bioavailability in corn production, leading to an enhancement in agricultural yield [98–100]. Others reported a decrease in soil salinity and sodicity [100], and improvement of saline soil due to liming potential [101,102].

**Table 3**
Proximate analysis and calorific value of biochar (750 °C and 2 h residence time).

| Proximate analysis | | | HHV |
|---|---|---|---|
| **Moisture (wt.%)** | Volatile matter (wt.%) | Ash content (wt.%) | (MJ/g) |
| **1.9** | 36 | 55 | 12.73 |

The electrical conductivity (EC) of the biochar was determined to be 634 μS/cm, which was lower than the EC measured in the initial feed sludge and accounted for 2029 μS/cm. It's worth noting that other researchers have also observed a reduction in EC following pyrolysis [103–105]. Conversely, some studies have reported an increase in the EC values of biochar when compared to the original feed sludge [106]. When assessing the suitability of biochar for soil application, the Food and Agriculture Organization (FAO) considers soils to be impacted by salts when their EC values exceed 2000 μS/cm [107]. Vilas-Boas et al. found that the soil amended with sewage sludge-derived biochar at application rates ranging from 2.5 wt% to 10 wt% did not exhibit elevated salinity levels. However, they cautioned that the potential risk of soil salinization due to biochar application should be subject to further investigation [108].

### *3.3.3. Heavy metals*

One of the primary concerns regarding the agricultural application of biochar is the accumulation of heavy metals in the soil. The concentrations of heavy metals in both the feedstock and the resulting biochar are presented in Table 4. Dried sludge (feedstock) in this experiment has domestic origin and the examined heavy metals aligns with values reported elsewhere for domestic sludge [109–111], but smaller than values reported by others [111,112]. Pyrolysis resulted in mass reduction -as calculated by equation 10- of Pb, Cu, Cr, Mo, Ni, and Zn by 65 wt%, 60 wt%, 48 wt%, 33 wt%, 28 wt%, and 28 wt%, respectively in biochar. In principle, there should be no releases of Cu, Pb, Cr, Ni, and Zn at temperatures up to 750 °C, given the vapor pressure characteristics of the predominant metal species, which include sulfides, carbonates, hydroxides, and organically bound metals [113]. Nevertheless, due to the anticipated high velocities of gas generated during pyrolysis, particles containing metals might be transported along with the gas stream, necessitating the inclusion of efficient particle collectors. It was noted that Cd evaporated at pyrolysis temperature of 625 °C and that residence time ranging 1hr to 4hrs caused a decrease in Cd in the carbonized sludge from 52% to 18% [113], while a pyrolysis temperature of 750 °C and 1hr residence time resulted in 95% metal evaporation. Other researchers reported a decline in the amounts of heavy metals in biochar and a rise in the amounts present in gas as pyrolysis temperature was augmented [114,115].

The concentrations of heavy metals in biochar are below both the recommended values by IBI and the permissible levels for fertilizers in Jordan, with the exception of selenium, as indicated in Table 4 T is worth mentioning that the selenium concentration in soils in the southern region of Jordan falls within the range of 1.19–1.54 mg/kg, as determined from soil samples collected from 12 separate domestic farms [118]; however, Se concentrations in non-arable soil in regions in the Central Jordan was found to be in the range of 1.6–17.5 mg/kg [119], while soil Se content reported worldwide averaged 0.40 mg/kg [120]. There is a scarcity of data on selenium concentration in soils in southern Jordan; therefore, further research is needed to establish the average concentration. It might be reasonable to set limits that does not cause any rise in the original Se concentrations in the soil. Otherwise, Se removal technologies might be necessary in order to meet the current Jordanian instructions. Concerning cadmium (Cd), it is uncertain whether its concentration in the biochar complies with the Jordanian Instructions for organic fertilizers. The measured value suggests concentrations below 5.0 mg/kg$_{dw}$, while the specified limit is 3.0 mg/kg$_{dw}$. Nevertheless, it is important to note that cationic heavy metals present in biochar exhibit strong stability and resistance to leaching. This resilience can be attributed to either the precipitation of cationic species with anions or the complexation of metal species with mineral oxides and organic carbon [121]. Lu et al. concluded that biochar generated by sewage sludge pyrolysis has low potential risk on soil and on groundwater when used as soil amendment [122]. Additionally, Li et al. documented a reduced bioavailability of heavy metals through the enhancement of biochar's adsorption capacity [123]. The leaching and bioavailability of heavy metals depend on the pH, redox potential, and organic matter content of the

**Table 4**
Heavy metals concentration in feedstock and produced biochar.

| Parameter | Feed stock mg/kg$_{(dw)}$[c] | Biochar mg/kg$_{(dw)}$ | Value (mg/kg$_{dw}$) defined by the Instructions No. G/6 of 2016 (Jordan Ministry of Agriculture)[b] | IBI recommended values mg/kg$_{(dw)}$ Range of maximum allowed thresholds[a] | Feed stock literature values mg/kg$_{(dw)}$[c] | | Biochar mg/kg$_{(dw)}$ | |
|---|---|---|---|---|---|---|---|---|
| | | | | | (1) [109] | (2) [116] | (1) [55] | (2) [117] |
| Chromium (Cr) | 39 | 41 | 100 | 93–1200 | 25 | 40 | 25 | 211 |
| Molybdenum (Mo) | 39 | 53 | | 5.0–75 | | | | |
| Lead (Pb) | 43 | 30 | 120 | 121–300 | 43 | 71 | 59 | 110 |
| Nickel (Ni) | 22 | 32 | 50 | 47–420 | 15 | 31 | 90 | 89 |
| Zinc (Zn) | 965 | 1408 | | 416–7400 | 1005 | 1261 | 1167 | 2020 |
| Arsenic (As) | <10 | <10 | 15 | 13–100 | | | 5.2 | BDL[d] |
| Mercury (Hg) | <1.0 | <1.0 | 1.5 | 1.0–17 | | 0.58 | <0.01 | |
| Cobalt (Co) | <5.0 | <5.0 | | 34–100 | | | | |
| Selenium (Se) | <10 | 13 | 4.0 | 2–200 | | | | |
| Cadmium (Cd) | <5.0 | <5.0 | 3.0 | 1.4–39 | 2.4 | 1.4 | 0.27 | BDL |
| Copper (Cu) | 183 | 149 | | | 111 | 457 | 543 | 552 |

[a] Range is based on standards for soil amendments or fertilizers from a number of jurisdictions.
[b] Instructions for licensing conditions for the production, processing, storage, circulation, trade and advertisement of agricultural fertilizers and plant growth regulators issued under article 20 of Agricultural Law No. 13 of 2015 and its amendments.
[c] $d_w$ dry weight basis.
[d] Below detection limit.

soil [110]. Chinese regulations, for example, have set pH related maximum allowable limits for heavy metals intended for natural use. The permissible limit for Cd is 5 $mg/kg_{dw}$ when the soil pH is below 6.5, whereas the limit increases to 20 $mg/kg_{dw}$ for soils with a pH higher than 6.5 [124]. When considering Mo, it is important to highlight that there have been minimal studies conducted on the immobilization of this metal in soils amended with biochar. However, Wang et al. reported a higher mobility of molybdenum in heavily Mo contaminated soils amended with a biochar supported nanoscale zero-valent iron [125]. Higher mobility and bioavailability at pH > 6.5 was also reported for Mo [126,127].

### 3.3.4. Nutrients concentrations

Biochar nutrients' contents are shown in Table 5. Around 20 wt% of the total nitrogen was lost during pyrolysis of sewage sludge at 750 °C due to loss of organic nitrogen, $NH_4^+$, and $NO_3$. Higher nitrogen losses were reported in literature during sewage sludge pyrolysis at elevated temperatures [128,129]. Phosphorus and potassium were concentrated in biochar as compared to sewage sludge raw material, which aligns with findings of other researchers [128,130]. Biochar originated by sewage sludge pyrolysis additionally improves soil phosphorus fertility [121], and reduces leaching of nutrients from soil [129]. Yu et al. found that soil available P increased by 5.6–38 times when sewage sludge originated biochar was applied to soil [131]. According to Jordanian instructions No. G/6 of 2016 outlined by the Ministry of Agriculture, organic fertilizers are required to have nitrogen, $P_2O_5$, and $K_2O$ content exceeding 2%, 0.9%, and 0.5%, respectively based on dry weight. Consequently, generated biochar might be considered as agricultural fertilizer with respect to its nutrients content. Nitrogen content of biochar produced at 750 °C and 2hrs residence time was found to be 5%, which might be of significance if biochar is used on arable lands [132]. For example, the application of biochar and a mixture of biochar-compost increased N availability and okra growth after 4 weeks of plantation [133]. However, some researchers indicated that high temperature pyrolysis limited the availability of N in the soil [78] possibly due to aromatic structure of organic compounds. Additional discussion on N availability is presented in the final discussion section.

### 3.3.5. Energy balance of pyrolysis at 750 °C and 2hrs residence time

Energy required for sludge drying was calculated to be 1438 kJ/kg a shown in Table 6, while energy required for pyrolysis at 750 °C was calculated to be 1150 kJ/kg. Hossain et al. calculated energy demand between 708 and 1180 kJ/kg for electrical furnace heating at 550 °C [136]. On the other hand, energy content measurements in this study showed that biochar has a HHV of 12.73 MJ/kg, which means that condensable and non-condensable volatiles contain 2.8 MJ/kg (biochar energy content subtracted from feed sludge energy content). Accordingly, and assuming a 60% energy efficiency for the system, both condensable and non-condensable volatiles will barely be sufficient to maintain the temperature of the furnace at 750 °C. In this case, additional energy source is required for sludge drying. Turek et al. investigated energy demand for sludge drying and pyrolysis for a full wastewater treatment plant and performed energy balance for different scenarios [43]. Their results showed that the total demand varies between 4003 and 5604 kJ/kg depending on the season. Moreover, their results also indicated that the plant would provide around 3360 kJ/kg, which is higher as compared with values estimated in this research. This might be attributed to the higher amounts of generated bio-oil and gas since biochar yield was estimated at only 36% [43].

It's important to emphasize that achieving an energy self-sufficient system primarily hinges on factors like the energy content of the input sludge, its moisture content, the temperature used during pyrolysis, and energy efficiency of the combustor. Schnell et al., indicated that at least 10 MJ/kg is demanded to operate the process, and therefore, feed sludge must be completely dry [6]. It's worth noting that forthcoming changes in EU regulations are set to require the utilization of energy for sludge containing dry matter with a lower heating value exceeding 6.5 MJ/kg [43], which could potentially enhance the commercial viability of sewage sludge pyrolysis. HHV of the bio-oil was measured to be 32.7 MJ/kg and is comparable with values ranging 33-36Mj/kg obtained by other researchers [62,137]. The HHV of the produced bio-oil is about 73% of that found in diesel, which accounts for 44.8 MJ/g [138].

**Table 5**
Nutrients content of the biochar.

| | Parameter | | | | | |
|---|---|---|---|---|---|---|
| | TN[a] (% dry wt.) | TKN[b] (%dry wt.) | $NH_4^+$ (%dry wt.) | $NO_3^-$ ($mg/kg_{dw}$) | TP[c] (%dry wt.) | K (%dry wt.) |
| Raw sludge (feedstock) | | | | | | |
| This study | 4.96 | 4.45 | 0.77 | 257 | 2.1 | 0.31 |
| A. Raj [134] | 0.94 | | 0.05 | 23 | 0.45 | 3.5 |
| J. K. M. Chagas [135] | 3.0 | | | | 3.6 | 0.08 |
| Biochar | | | | | | |
| This study | 3.99 | 3.25 | 0.13 | 28 | 3.2 | 0.60 |
| H. Yuan [129] | 0.91 | | | | 4.9 | 1.6 |
| A. Raj [134] | 0.11 | | | | 0.55 | 3.9 |
| J. K. M. Chagas [135] | 2.3 | | 0.02 | 5.8 | 6.1 | 0.13 |

[a] TN is total nitrogen.
[b] TKN is the total kjeldahl nitrogen.
[c] TP is total phosphorus.

**Table 6**
Energy demand for sludge pyrolysis and energy content of end products.

| | Energy demand (kJ/kg) | | | Energy content (kJ/kg) | |
|---|---|---|---|---|---|
| | Sludge drying | Sludge pyrolysis | Total demand | Biochar | Bio-oil |
| This study | 1438<br>Eqs. (1)–(7) | 1150<br>Eq. (8) | 2588 | 12730<br>Eq. (9) | 2800 |

*Maximum average daily values and the values present the demand of the full wastewater treatment plant.

## 4. Final discussion

### 4.1. Anticipated additional benefits of biochar as soil amendment

In addition to the previously discussed points, it has been reported that pyrolysis contributes added value to soil properties. For instance, a review on biochar application to Mediterranean soils -known to be vulnerable to water scarcity and loss of organic matter-concluded that biochar can effectively improve soil water content under limited water conditions during summer and drought periods due to its potential to store carbon [139]. Water holding capacity was reported to improve in soils amended with biochar produced at high temperatures of 800 °C compared with biochar produced at lower temperatures [140,141]. Biochar amendment was also reported to enhance soil aggregate stability and consequently improves soil stability and reduces runoff and erosion of soil organic carbon [142]. Additionally, biochar originated from sewage sludge had a low risk of soil and groundwater contamination and can be safely used for agricultural applications [134]. Pyrolysis, among other processes [143], was also reported to destroy the DNA and accordingly eliminate antibiotic resistance genes and mobile genetic elements present in feedstock and consequently no impact is expected neither on the abundance of antibiotic resistance genes nor on microbial community in soils amended with biochar [144].Sludge pyrolysis at high temperatures is favorable since produced biochar has more stable organic matter structure compared with biochar produced at lower temperatures [145]. Biochar application to soil was also reported to enhance mineral content (ash content), which can provide significant agronomic benefits [146].

Limited research exists on the long-term effects of biochar derived from sewage sludge on soil characteristics and its subsequent implications on plants. For instance, nine years of low-dose (0.23 t $ha^{-1}$) of biochar application positively impacted nitrogen transformation by mitigating nitrification rate and leading to higher crop yields [147]. In a long-term field experiment of 6 consecutive years, it was found that biochar application to rice-wheat cropping system together with fertilizers (N and P) improved soil physical properties and aggregate stability leading to better crop growth regardless of the biochar application rate (20 and 40 t $ha^{-1}$) [148]. Chagas et al. reported that heavy metals' content in soils remained below the maximum permissible limit of different international regulations 5 years after field trials [149]. Additionally, the application of biochar for two consecutive years to loamy sand soil cultivated with peanuts demonstrated enhancements in the soil microbial community and resulted in a maximum crop yield increase of 60.43% [150]. In general, biochar derived from sewage sludge possesses a long-term capability to improve the physical and chemical properties of soil, directly influencing the growth of plants [151,152]. A one-year sewage sludge biochar application to agricultural land contributed also to increased macronutrient uptake by corn and in a high grain yield that might compete mineral fertilizers [153]. Moreover, biochar provided nutrients to soil with a residual effect of at least three years when applied at a rate of 30 t $ha^{-1}$[135] since it was able to provide adequate P for corn uptake at least for three years. However, biochar did not meet K demand and additional mineral fertilizer was needed. Treatment of sludge before pyrolysis might also be used to improve K content of the biochar [154].

Nevertheless, it's important to recognize that the interaction among biochar, soil, and plants is an intricate process, influenced by the specific properties of both the biochar and the soil, as well as the choice of crop [147,155,156]. Application rate of biochar shall take soil type and environmental conditions [147] into consideration, and accordingly, comprehensive and long-term investigations are critical before making conclusive statements about the effects of biochar on soil and its related agricultural benefits. Moreover, the impact of gradual loading of metals to soil and their accumulation needs further investigations.

### 4.2. Practical implications and scale-up of the obtained results

Approximately 90% of Jordan's area experiences an average rainfall of less than 200 mm and is characterized as rangelands (Badia). These areas feature indigenous plant growth and are considered crucial for agro-pastoralism; however, they are not deemed suitable for crop cultivation due to various factors, such as limited rainfall, inadequate soil fertility, rugged terrain, and rocky terrain [157]. Additionally, the Badia soil has suffered severe degradation as a result of overgrazing by small ruminant herds [158], urbanization, climate change, and poor land management [157,159]. Extensive portions of the Badia are undergoing a transformation into sparsely vegetated landscapes with a crusted soil surface [160]. Accordingly, rehabilitation of these areas is crucial to improve vegetation cover grazing [159], increase availability of medicinal plants [161], enhance water recharges [158], and reduce sediments transport and thus control erosion [162]. Better management suggested for the rangelands in Jordan include increasing the rangeland reserves, management of vegetation cover [163], and water harvesting [159]. Moreover, the use of organic amendments was recommended to improve physical and chemical characteristics of the rangelands [164]. Elsewhere, biochar was examined for its potential in restoration projects to improve soil moisture for species and results indicated its potential in increasing soil moisture provided that proper application methods are used [165]. Moreover, and as discussed earlier, some researchers showed the positive impact of biochar application to reduce soil erosion, which is attributed to biochar bonds with soil mineral surfaces through carboxyl and phenolic functional groups, consequently improving the structural aggregation and soil stability [166].

Wadi Musa WWTP can be considered as a pilot plant in which biochar produced after sludge pyrolysis is used for rangelands rehabilitation. The WWTP is one of the small-scale treatment plants in the country and was designed to serve mainly the touristic area of Petra in addition to surrounding villages with a design capacity of 3400 $m^3$/d. The annual estimated amount of generated sludge on the year 2035 is 550 tons based on dry matter [3]. The current sludge management practice in Wadi Musa WWTP is sludge piling within the same plant after solar drying in sludge drying beds. The plant lacks storage area, not mentioning the environmental impacts during rainy season and windy days. Based on the obtained results of this research, a pyrolysis plant operated at 750 °C and at 2 h retention time would result in the production of 275 tons/year (50% biochar yield) [3]. This value can be regarded as the highest amount achieved annually, given that the plant is presently generating a lower quantity [3]. The rangelands existing in 5 km radius to the east of the treatment plant has an area of 61 $km^2$ and biochar soil amendment can be a good choice to improve soil physical and nutritional properties (Fig. 4). An application rate of 30 tons/ha would require an area of 1 $km^2$ for the entire amount of sludge produced until the year 2035. This area is 1.6% of the rangelands present in the neighborhood of the plant and worth to be considered by the Jordan Ministry of Agriculture for piloting the long-term impact of biochar soil amendment on rehabilitation of the rangelands in Jordan.

## 5. Limitations of this research

It is important to mention that all analysis were conditionally conducted in accredited laboratories, and accordingly, the cost of analyses was considerably higher than what would be spent if analyses were conducted by the project team. Since the budget was limited, replicates of experimental runs were not performed within the framework of the project. However, thorough discussions were made and supported by literature evidence. Moreover, this research did not cover seasonal variations in sewage sludge quality and energy calculations were made based on the analyzed samples only. In fact, variation in sewage characteristics might be one of the main limitations that needs to be addressed in future research.

## 6. Conclusions and recommendations

Sewage sludge pyrolysis was carried out at temperatures of 500 °C, 600 °C, 750 °C, and 850 °C, with three distinct residence times for each temperature setting. The results revealed that temperature is the primary factor influencing the production of end products. As the pyrolysis temperature rose from 500 °C to 850 °C, the biochar yield declined from 59% to 48% (dry weight basis). Likewise, the yield of bio-oil exhibited a noticeable decrease with increasing temperature, particularly at residence times of 2 h and 3 h.

In the analysis of the tested sewage sludge, a stable carbon, as defined by the International Biochar Initiative, was achieved at a pyrolysis temperature of 750 °C and a residence time of 2 h. The $(H/C_{org})^{at}$ ratio measured at 0.54 was lower than the recommended threshold of 0.7, signifying the presence of stable carbon. Further examination of the resulting biochar revealed several noteworthy findings. The pH increased from 6.47 in the raw feed sludge to 8.33 in the produced biochar with a liming potential of 26% as $CaCO_3$. Electrical conductivity decreased from 2029 μs/cm for the feed sludge to 634 μs/cm in the biochar. Moreover, the concentration of heavy metals in the biochar fell within the lower limits recommended by the International Biochar Standards, with levels of Mo, Cr, Pb, Ni, Zn, As, Hg, Co, Se, Cd, and Cu measuring 41, 53, 30, 32, 1408, <10, <1.0, <5.0, 13, <5.0, and 149 $mg/kg_{dw}$, respectively. Regarding nutrients' content, the produced biochar and based on dry weight contained 3.99% TN (Total Nitrogen), 3.2% TP (Total Phosphorus), and 0.6% TK (Total Potassium). Additionally, the energy content of the generated condensable and non-condensable volatiles will be sufficient to maintain the temperature of the furnace at 750 °C, while additional energy source is required for sludge drying.

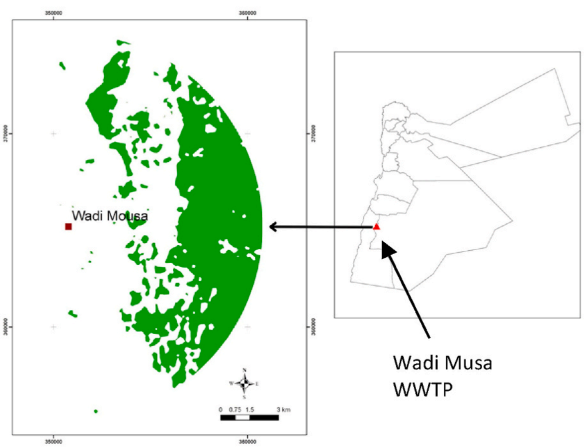


**Fig. 4.** Rangelands existing in 5 km radius to the east of Wadi Musa WWTP.

The pyrolysis process presents a promising approach to sludge treatment, potentially reducing sludge volume by at least 50% on a dry weight basis, thereby cutting down on subsequent management expenses. The resultant biochar can serve as a valuable source of carbon and nutrients for soil enhancement, agricultural production, or agro-pastoral applications. Nonetheless, further research is essential to gain a more comprehensive understanding of the interactions between biochar and soil, especially in terms of their long-term effects.

## Data availability statement

Raw data associated with this research were not deposited into a publicly available repository; however, data will be available by the corresponding author upon request.

## Disclaimer

The publication has been produced as a result of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH implemented project “Sustanable Sludge Management” -SSM activities. On behalf of the German Federal Ministry for Economic Cooperation (BMZ).



## Ethics statement

Informed consent was not required for this study because the contents do not demand informed consent.

## CRediT authorship contribution statement

**M. Halalsheh:** Writing – original draft, Supervision, Project administration, Methodology, Formal analysis. **K. Shatanawi:** Supervision, Project administration, Formal analysis. **R. Shawabkeh:** Supervision. **G. Kassab:** Writing – review & editing, Validation, Methodology. **H. Jasim:** Project administration. **M. Adawi:** Resources, Investigation. **S. Ababneh:** Supervision, Funding acquisition, Conceptualization. **A. Abdullah:** Supervision, Funding acquisition, Conceptualization. **N. Ghantous:** Supervision, Funding acquisition, Conceptualization. **N. Balah:** Supervision, Funding acquisition, Conceptualization. **S. Almomani:** Supervision, Funding acquisition, Conceptualization.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to improve readability. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

## 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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