Pyrolysis of Biosolids to Produce Biochars

Subjects: Engineering, Chemical | Others

Contributor: Samar Elkhalifa , Hamish R. Mackey , Tareq Al-Ansari , Gordon McKay

Biochar is a solid, charcoal material that can be used in different applications such as its use in agriculture as a soil enhancer in which moisture content is sustained for long periods of times. Biosolids or biosludges will refer to any form of sludge that has undergone some form of treatment (e.g., chemical, biological, heat treatment, etc.) in order to transform it into a less hazardous and organic form. More importantly, there seems to be an inconsistency in defining what classifies as biosolids, hence, a unified definition is established and provided. The aim is to enable the scientific community as a whole to use a standard definition that allows for synergies to take place. Specifically, the pyrolysis process is selected and is known as a thermochemical technique in which heat and an oxygen-free environment facilitate the decomposition of the feedstock into different products, depending on the operating parameters.

pyrolysis biosolids biochar waste management sustainability circular economy

energy bio-oil biogas

1. Biosolids/Biosludge

The world is experiencing an accelerated level of advancement in which people aim at enhancing their living standards, while competing for food, water, and energy. This threatens the availability of enough resources for future generations, hence hindering the achievement of sustainability goals. As a result of inequalities and mindless consumption, wastes are generated in abundance impacting the environment and transgressing the Earth into undesired shifts from its equilibrium (i.e., its balance). Waste management, hence, plays a pivotal role in alleviating the suffering of the environment, and contributes to the prosperity of societies. Examples of typical waste management techniques include landfilling and incineration, both are associated with technical and environmental difficulties. There are other techniques including the application of methods that implement the concept of circular economy, where wastes are reused as input for the production of various commodities thus creating a market for waste.

Biosolids or biosludges will refer to any form of sludge that has undergone some form of treatment (e.g., chemical, biological, heat treatment, etc.) in order to transform it into a less hazardous and organic form. Additional forms of SS resulting from industrial activities involving the above are also considered (e.g., due to the use of a bioreactor or from the pharmaceuticals industry). **Figure 1** is an illustration of the different classes of biosolids.

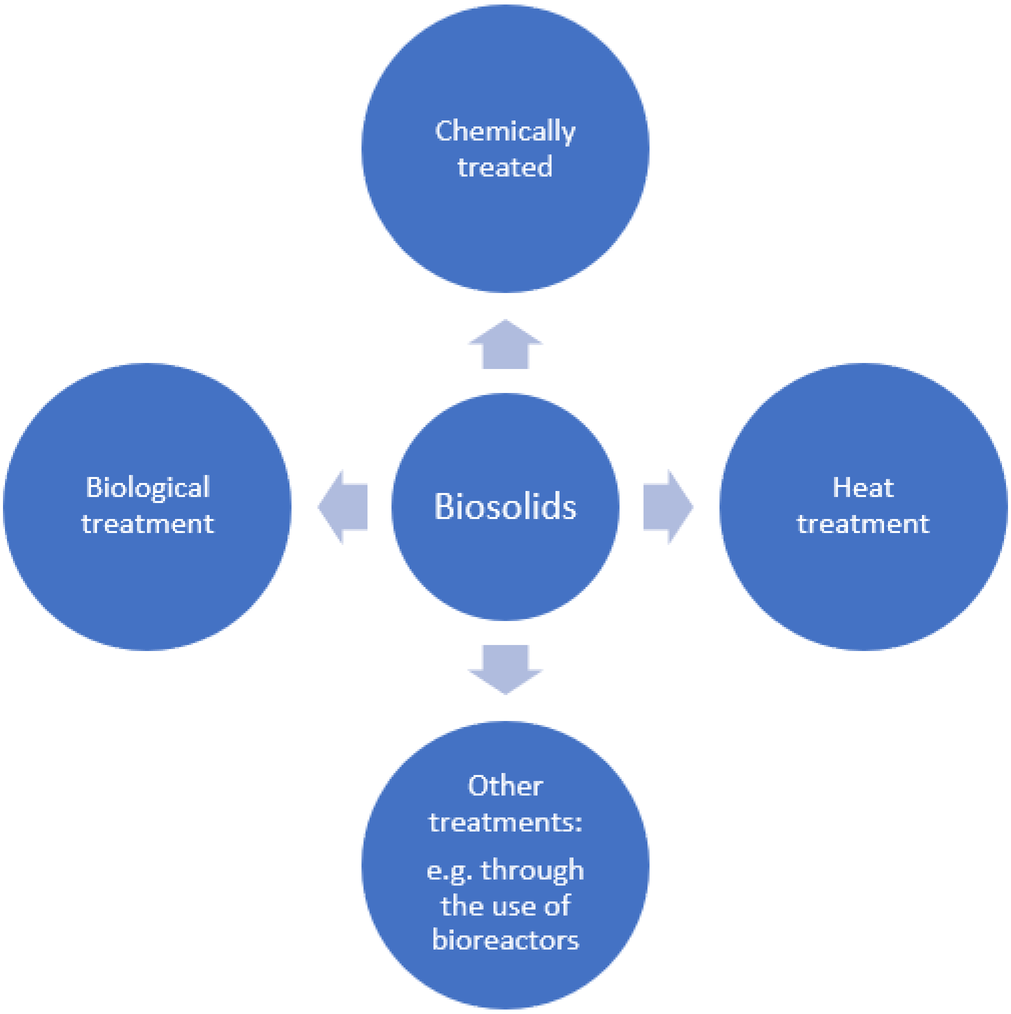

Figure 1. Different classifications of what constitutes biosolids

The pyrolysis process holds great potential as a thermal treatment method [1][2], that is capable of transforming biomass into value-added products. Typically, a biomass feedstock will undergo thermal treatment to an elevated temperature that goes beyond 400 °C in the pyrolysis process in an inert environment, that involves partial or total removal of oxygen. In addition to containing the gas produced resulting from the thermal degradation of the organic components [3][4], the pyrolysis process results in the production of three major products, namely, biochar, bio-oil, and biogas.

2. Management of Biosolids and the Use of the Pyrolysis Process

Solids resulting from wastewater are either applied to land as soil amendment and nutrient source, incinerated, or landfilled [5]. These solids are full of micropollutants that include organic chemicals originating from consumer-based products, which end up in the sewer drains during disposal (e.g., pharmaceuticals, antimicrobial compounds, personal care products, medicines and hormones, etc.) [6][7]. Therefore, the sewage sludges and wastewater treatment sludges and their by-products from these locations require new and innovative handling methods that alleviate environmental burdens, while producing value-added products, e.g., capacitors [8]. The thermal process of pyrolysis to biochars has been reported to combat some of these issues, for instance, the destruction of organic molecules, the destruction of microorganisms and the fixation of heavy metals, preventing them from leaching out into the soil.

3. The Pyrolysis Process

Pyrolysis is a relatively uncomplicated technology requiring no complex process plant compared with incineration and gasification and it is quite environmentally friendly [9]. Additional benefits include its ability to handle many waste types [10], while directly producing several product materials (for example, biochars, bio-oils and syngas) [11][12]. In terms of the limitations of the sustainability of the pyrolysis process for a treatment alternative, the issue for wet biosolids feedstock is a problem but it has been stated recently that the introduction of low-cost pre-drying solutions can improve the outcomes, prior to pyrolysis [13]. For example, solar drying methods are promising techniques as a low-cost drying pretreatment in arid environmental conditions, having plentiful sunlight and a low humidity environment. Alternatively, flue gases, available from the combustion of the bio-oils/biogas, in the temperature range 140–180 °C could achieve the same objective and even indirect heat exchange with the hot outlet pyrolysis gases. The pyrolysis process is classified into different types with the slow and fast pyrolysis being among the most commonly applied types (**Figure 2**).

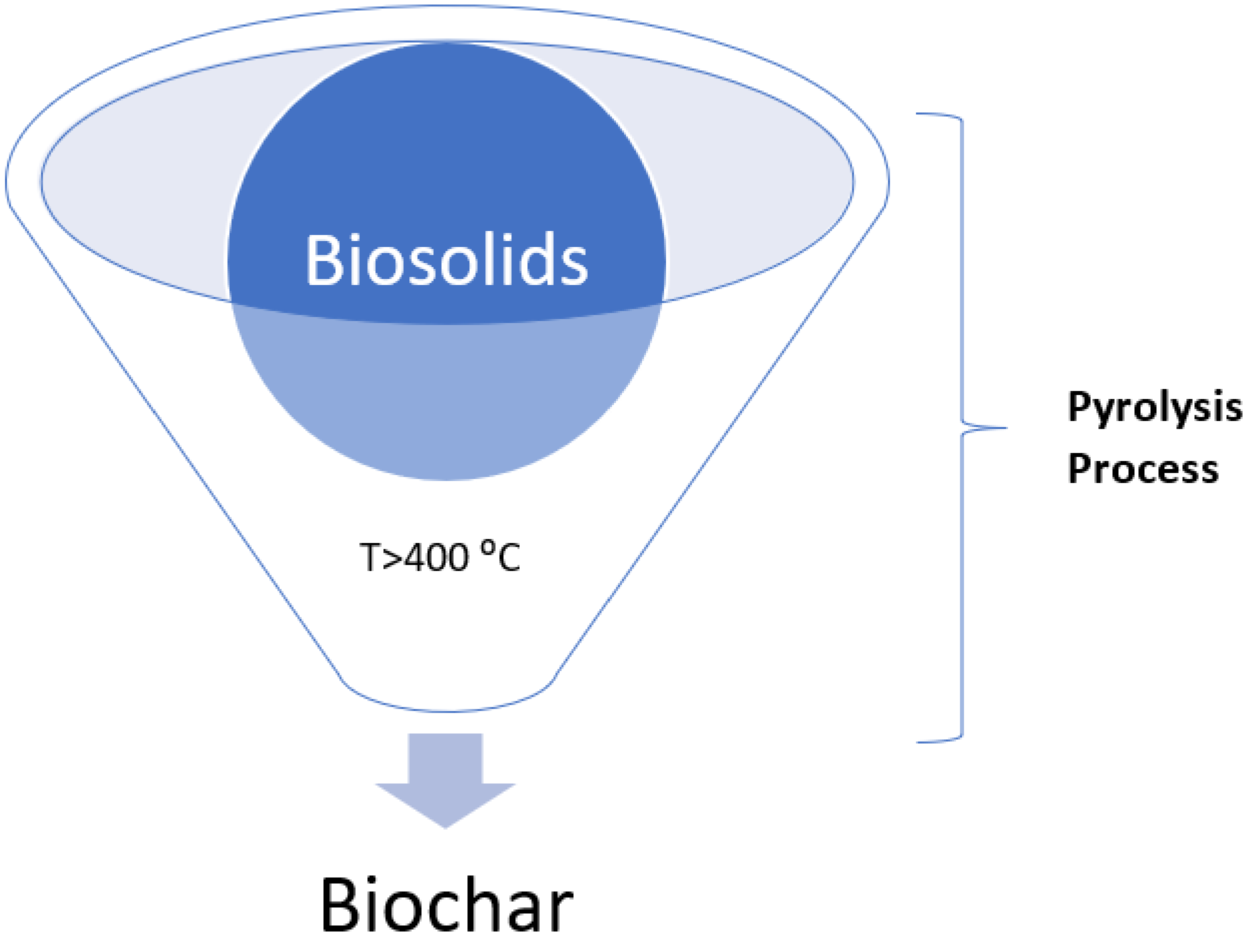

Figure 2. Depiction of the pyrolysis of biosolids

4. Benefits of Pyrolysis

Pyrolysis is a relatively uncomplicated technology requiring no complex process plant compared with incineration and gasification and it is quite environmentally friendly [14]. Additional benefits include its ability to handle many waste types [15], while directly producing several product materials (for example, biochars, bio-oils and syngas) [16][17]. In terms of the limitations of the sustainability of the pyrolysis process for a treatment alternative, the issue for wet biosolids feedstock is a problem but it has been stated recently that the introduction of low-cost pre-drying solutions can improve the outcomes, prior to pyrolysis [18]. For example, solar drying methods are promising techniques as a low-cost drying pretreatment in arid environmental conditions, having plentiful sunlight and a low humidity environment. Alternatively, flue gases, available from the combustion of the bio-oils/biogas, in the temperature range 140–180 °C could achieve the same objective and even indirect heat exchange with the hot outlet pyrolysis gases.

5. Limitations of the Pyrolysis Process

The pyrolysis process, whether fast or slow, is associated with a number of challenges which have been recently discussed in the work of [19] who has explored the use of wet biomass for bioenergy production. Briefly, the use of fast pyrolysis is typically associated with the requirements for dewatering or drying [18] stages, in addition to the resulting low yield and poor quality bio-oil. It also places significant pressure on vapor condensation and the gas cleaning system. Slow pyrolysis is also associated with a number of challenges that need remediation steps that are also outlined in the work of [19]. Such limitations include high energy requirements of the process in addition to the requirements for vapors separation and gas cleaning systems.

6. Treatment of Sludge Prior to Pyrolysis

Most of the studies focus on the pyrolysis process itself and the characterization of the end-products, while assigning minimal reference to the major pretreatment requirement of the sludge that was obtained prior to the pyrolysis. Mostly, these studies indicate that the biosludge was received in a dry form with certain characteristics [20][21]. Furthermore, some studies report further drying of the obtained sludge, such as the work of [22], who obtained their sludge from a printing and dyeing plant. In Poland, [23] obtained sewage sludge (SS) from two municipal wastewater treatment plants (WWTPs) based on MBT; mechanical and biological treatment. After the sewage sludge anaerobic digestion process in the WWTPs, samples of the sewage sludge were harvested in summer, at the final processing stage. Another treatment of sewage sludge was reported by [24] who implemented a triple oxidation ditch processing stage for the wastewater treatment step.

Another problematic sludge is oil sludge from oil refineries [25]. Initial efforts to make use of this sludge sought to convert it into useful resources such as lower molecule organic compounds and carbonaceous chars by the application of pyrolysis, but with very limited success [26]. In a later study, the oil sludge was the feedstock for the pyrolysis reaction which resulted in a unique product distribution and characteristics. **Table 1** provides a summary of the recent work on the pyrolysis of treated sewage sludge and other biosludges.

Table 1. Previous studies on the pyrolysis of treated sewage sludge.

Pyrolysis Method	Feedstock Type	Process Conditions			Products			References
		Temperature	Time	Pressure	Char	Oil	Gas	
Slow pyrolysis	Air-dried biosolids	300 °C and 500 °C	Residence time of 30 min	-	86 ± 8 and 65 ± 4%	-	-	[64]
Slow pyrolysis	Three different biowastes	550 °C	Held for 1.5 h	-	18.6%	-	-	[65]

Pyrolysis Method	Feedstock Type	Process Conditions			Products			References
		Temperature	Time	Pressure	Char	Oil	Gas	
	including biosolids							
Microwave assisted pyrolysis in a customised single-mode microwave chamber connected to a 1.2 kW microwave source	Biosolids	600 °C	Holding time of 10 min	-		-	-	[66]
Fast microwave-assisted	Continuous biomass (SS)	450–600 °C	-	-	63–34%	17–26%	20–40%	[67]
Microwave pyrolysis technology	Biosolids	The quartz crucible outer temperature was reported in the range 300 °C to 350 °C immediately after each experimental	-	-	59.93%	2.37%	37.7%	[68]

Pyrolysis Method	Feedstock Type	Process Conditions			Products			References
		Temperature	Time	Pressure	Char	Oil	Gas	
		run; but the sample temperatures were in the range 600 °C to 650 °C						
Microwave assisted pyrolysis in a customised single-mode microwave chamber connected to a 1.2 kW microwave source	Biosolids	300–800 °C	Mean residence time of 6.38 s for the nitrogen in the pyrolysis chamber	The control valve was manually adjusted to maintain the pressure within −15 kPa gauge pressure	0.91–0.77 g	-	-	[69]
Slow pyrolysis	Biosolids	300–750 °C	-	-	67.5 ± 1.2 to 48.1 ± 0.4% and 70.1 ± 1.2 to 44.4 ± 0.2	-	-	[70]

Pyrolysis Method	Feedstock Type	Process Conditions			Products			References
		Temperature	Time	Pressure	Char	Oil	Gas	
Co-pyrolysis	Anaerobically digested and thermally dried SS	525 °C	-	1.01 × 10^5 Pa	28%	58%	14%	[71]
Co-pyrolysis	A triple oxidation ditch process was used for wastewater treatment and the SS feed samples were taken from the dewatering stage	400–600 °C	Pyrolysis for 1 h	-	44.5–44.1%	-	-	[61]
Flash pyrolysis	Anaerobically digested and thermally dried sewage sludge	450–600 °C	1 s vapor residence time	-	24–10%	70–73%	5–17%	[72]
Slow pyrolysis	Four different anaerobically digested sewage sludges	500–700 °C	Pyrolysis time of 5 hr	-	Ranged from 54.5 to 40.2%	-	-	[73]
Fast pyrolysis	Biophysical dried sludge	500–900 °C	-	-	63.10 ± 0.50 to	-	-	[74]

Pyrolysis Method	Feedstock Type	Process Conditions			Products			References
		Temperature	Time	Pressure	Char	Oil	Gas	
					53.31 ± 0.48%			
Slow pyrolysis	Digested wastewater sludge/biosolids	300–700 °C	-	-	72.3 ± 2.5 to 52.4 ± 2.6%	-	-	[75]

7. The Potential for Energy Recovery from the Pyrolysis Bio-Oil and Biogas

It is important to take into account the two major by-products, biogas and bio-oil, because their effective utilization will have a tremendous benefit on the economic attractiveness of the pyrolysis process package [27]. Besides biochars, the pyrolysis products from biosolids include bio-oil and biogas, which are associated with the energy content that can be potentially recovered and utilized. **Table 2** presents a summary of high calorific values or higher heating values (HHV) reported by several studies.

Table 2. HHV of bio-oil and biogas from the literature.

Reference	Bio-oil HHV	Biogas HHV
[107]	27.8–31.4 kJ/kg in nitrogen and hydrogen atmosphere	-
[108]	12.19–22.32 MJ/kg	-
[109]	Energy yield of 1042–7762 kJ/kg-fuel	Energy yield of 22–3745 kJ/kg-fuel
[110]	25.1 MJ/kg	-

[111]	23.9–27.9 MJ/kg	13–17.5 MJ/kg
[112]	36–39 MJ/kg-oil	-

The study conducted by [28] report the HHV of bio-oil and char only, where HHV of 36–39 MJ/kg-oil was observed for the process. The HHVs were not influenced by the operating temperatures nor the sludge type as per the study. Another promising results were demonstrated by the work of [29] in which the energy content of biogas and bio-oil was always greater than the energy required for the pyrolysis study.

Woody and non-woody biomass materials were used in the production of bio-oil and biochar, with the investigation of HHV of both products [30]. The HHV of bio-oil was comparable to other studies mentioned in Table 2, with values in the range 12.19–22.32 MJ/kg. It is evident that the slight variations in the reported values for HHV are due to the type of biomass used, its composition and the type of pyrolysis used. Moreover, bio-oil HHV was influenced by the inert environment used with heating value increasing from 27.75 MJ/kg to 31.40 MJ/kg when using nitrogen and then hydrogen in the work of [31]. The results imply the importance of the type of gases in the subsequent values of HHV of bio-oil products.

The energy recovery from both streams comes with some challenges. For instance, the liquid oil is heterogenous with fractions that contain dissimilar HHV [32], in addition to being a corrosive material. It is, however, a very attractive source of energy when compared to both the gas and char products' energy content. The inclusion of the by-products into the economic analysis can improve the economic effectiveness by 2 or 3 fold [27].

8. Benefits of Biosolids-Derived Biochars

It is crucial to distinguish between biochars produced from biosolids and those obtained from other types of biomass materials. There are commonalities in the uses of all types of biochar and as such the same benefits are expected from biosolids-derived biochars. From the results of previous work on biochars produced from other types of biomasses, the different biochar products were found successful for use in amending soils in commercial potting soil mixes, green roofs, and commercial agriculture [5]. However, the same benefits from biochars derived from biosolids require further research to determine its applicability, opening room for more research opportunities in the applied side of this type of research.

Furthermore, the addition of different biochars to soils promotes plant growth. This addition is associated with interesting biological and chemical changes such that a shift in rhizosphere microbial and fungal communities to more favorable compositions for plant growth is attained. The same changes can be achieved through the contribution of some chemicals to the soil-system that lead to similar increases in nutrient concentrations [5][33][34].

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