Biochar production from sewage sludge and microalgae combination: properties, sustainability and possible role in a circular economy

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Abstract

One possible destination for sewage sludge sustainable disposal is the production of biochar, that can be achieved by post-processing of the sludge itself, i.e. by pyrolysis. Biochar from sludge is considered one of the most interesting products in a wastewater treatment based circular economy, as proven by the multitude of possible uses so far tested in different areas. Recently, combined AS-microalgae systems have been proposed to recover both carbon and nutrients from wastewaters as alternative to conventional technologies such as those based on AS only. This could be efficient from the point of view of removal of mandatory components from wastewater effluents, but it adds potential issues to the problem of residue disposal. While in fact a consortium of microalgae and bacteria will prevail in the reactor as a function of the wastewater composition, environmental conditions, reactor design, and operation conditions, bacteria in the culture will oxidize the organic matter to inorganic compounds, consuming oxygen in this step, whereas microalgae use the light to uptake the inorganic nutrients that have been released by the bacteria and produce biomass, in turn releasing (some of) the oxygen required by bacteria for the oxidizing step. Although quite efficient for the liquid treatment stream side, such integrated systems seem to generate a residue that is apparently difficult to dispose of, as algae normally respond poorly to traditional, mechanical drying processes. In this study, alternative solutions for such disposal were investigated, by pyrolysation of a mixed sludge/bioalgae matrix under different conditions: in such way, not only landfillable residuals are practically eliminated, but a material with multiple possible end uses is generated. Starting materials (algae, sludge and combinations of both) and end-products (biochar and bio-oil) were physically and chemically characterized after pyrolysis under different conditions. Algae alone were also subject to preliminary solvent oil extraction to verify whether an increased biochar production would result from the modified process (which did, improving biochar generation by 25-33%). A comprehensive discussion on properties of end products as function of process design, possible applications and advantages of co-pyrolysis follows.

Keywords

Slow pyrolisis – Microalgae – *Chlorella* – Biochar analysis – Bio-oil – Sewage sludge disposal

Introduction

Sewage sludge is the final by-product of wastewater treatment in the integrated water cycle, its production is index of management efficiency of municipal and industrial wastewater treatment plants (WWTP). The volumes of excess sludge require additional treatment, disposal or final recovery in order to comply with current EU sanification objectives (Neczaj and Grosser, 2018). The cost of these processes has been estimated around 50% of the total cost of wastewater treatment (Callegari and Capodaglio, 2018). Italy, among the other EU countries, is required to improve quality of wastewater treatment effluents and update the facilities or proceed with the installation of new treatment plants where necessary, under penalty of EU sanctions. For this reason, in addition to the demographic growth, the production of sewage sludge is destined to increase. The problem of disposal is therefore a very important obstacle.

However, the alternatives for sludge disposal turn out to be limited, since the accumulation of heavy metals, organic pollutants and pathogens narrow the use of techniques such as direct shedding in agriculture, composting and anaerobic digestion (Mantovi et al., 2005).

An energy favouring and economically appealing alternative would be incineration, which, in addition to significantly reduce the quantities of waste to be disposed of, allows cogeneration (Herbert and Krishnan, 2016). However, incineration involves high costs due to gas effluent treatment, to reduce the concentration of pollutants in compliance with regulatory limits. Therefore, the researchers' interest has switched to other innovative technologies, such as pyrolysis and gasification, conducted in absence or depletion of oxygen, leading to a significant decrease in fumes production and volume (up to 50% in pyrolysis). Pyrolisis also provides for transformation of waste treated in a solid component called biochar, and a component liquid called bio-oil (Callegari and Capodaglio, 2018).

These products can be used for different purposes, in particular biochar can be used as a fuel solid, as a soil conditioner for agricultural land, or can be applied in contaminated sites. Also, with the high temperatures of pyrolysis processes, the stability of metals present in sewage sludge is increased, reducing the possibility of potential leaks of these (Callegari and Capodaglio, 2018). About the energetic aspects, bio-oil and biochar can be used as fuels, meeting the increasing need for primary energy, since the demographic increase has led to a sudden exploitation of the fossil fuels (Lakaniemi et al, 2013). Consequently, the alarming increase in the concentration of carbon dioxide and other greenhouse gases in the atmosphere have caused a global rise of temperatures (Solomon et al., 2009). Industrialization, demographic growth, urbanization and transport development are all based on intensive coal, oil and natural gas exploitation. Another important aspect to consider is the availability of these resources, which will tend to run out over the years (Chisti, 2008).

Studies on use of new non-exhaustive, economically advantageous and less impacting resources is becoming more and more central in researchers' interest, in particular biofuels derived from biomass (Bilgili et al., 2017).

In this context, microalgae emerge as third generation feedstock for biofuels production (Chen et al., 2011). Microalgae are unicellular photosynthetic microorganisms capable of fixing carbon dioxide performing photosynthesis, and present numerous characteristics that make them suitable to be applied for energy purposes (Ahmad et al., 2011,). Amongst them: (i) absence of competitiveness with the food market, (ii) high productivity with reduced cultivated surface (microalgae allow to obtain an oil production of about 70% by weight of dried biomass, furthermore is required only 0.1 m^2 per year soil per kg of biodiesel), (iii)use of unusable surfaces for cultivation of different biomasses, not subtracting soil from food crops, (iv) the possibility of application with different types of water (fresh water, brackish water and wastewater). Microalgae present also a positive impact on carbon dioxide emissions, microalgal biomass contains about 50% of carbon over dry weight, which is derived mainly from CO_2. To produce 100 tons of microalgae allows to fix about 183 tons of carbon dioxide (Sánchez et al., 2003).

The high reproduction speed and ease of cultivation makes them more appealing if compared with other biomasses, as they allow to reach high yields in terms of bio-oil and biochar, also thanks to their high lipid content e low ash content (Yu et al., 2017). Numerous studies have aimed to determine the oil yield for biodiesel production, and the results were very satisfactory (Chisti, 2007, Reen et al., 2018, Chaiwong et al., 2013). Growth and productivity of microalgae are strongly influenced from environmental and physiological factors such as temperature, pH, light intensity, nutrient availability and finally, on levels of carbon dioxide (Kumar et al., 2018).

Microalgae, if grown in wastewater, can recover directly the nutrients needed for their growth, obtaining the dual benefit of biomass production and wastewater treatment. Recently, combined AS-microalgae systems have been proposed to recover both carbon and nutrients from wastewaters as alternative to conventional technologies. The cultivation of microalgae in wastewater allows the recovery of nitrogen and phosphorus contained in them, producing up to 1 kg of dry biomass per m^3 of wastewater (Ficara et al., 2014). This technique has been proposed as an alternative to conventional technologies, like the activated sludge treatment. Bacteria present tend to oxidize the organic substance contained in the wastewater into inorganic compounds consuming oxygen, while microalgae use sunlight to absorb inorganic nutrients released by bacteria, producing oxygen subsequently used by the bacteria for the oxidation.

The characteristics of the consortium can vary widely, depending on the conditions present in the reactor, but the fundamental element for growth appears to be the availability of light within the reactor. The process based on the use of microalgae consists of several phases: (i) effluent pretreatment, (ii) nutrient recovery and biomass production within photobioreactors, (iii) biomass collection, with recirculation or disposal of treated water and finally, (iv) transformation of the biomass into desired final products (Gabriel et al, 2018). Although quite efficient for the liquid treatment stream side, such integrated systems seem to generate a residue that is apparently difficult to dispose of, as algae normally respond poorly to traditional, mechanical separation and drying processes .The collection phase remains the phase more critical, since microalgae cells are small (2-20 μm), have a density similar to that of water, and a concentration in the wastewater rather low (0.5-0.3 g L^{-1}) (Gabriel et al, 2018).

The purpose of this paper is to evaluate biochar and bio-oil production through pyrolysis process starting from two initial materials: microalgae and sludge from wastewater treatment plants, determining which condition is more favourable to recovery of valuable products.

2. Materials and methods

Three different materials have been tested throughout the experiment, characterized and then pyrolyzed at two different temperatures. Both starter materials and solid products have been characterised using thermogravimetric analysis (TGA) and infrared spectroscopy (IR), HHV (higher heating value) in biochar samples has also been evaluated.

2.1 Samples preparation and pretreatment

A mixed culture of microalgae *Chlorella* has been cultivated in four lab-scale open reactors (0.35*0.20*0.10 cm) in a BG-11 medium, and kept at a constant high level of 3 cm. Air has been provided by a fishtank aerator to keep the microalgae suspended in the mixture, while light has been provided by a conventional warm light LED bulb (40 W) under light/dark ratio 16:8. Once the culture has reached stable growth, microalgae have been harvested and dried on nylon filters (ø = 0.25 μm) for 12 h. The size of agglomerated dried microalgae has been reduced and uniformed using a mortar.

Sewage sludge (a mixture of primary and secondary sludge) has been collected from a nearby wastewater treatment plant, then dried in oven at 100°C for 12 hours and stored until use (humidity content below 10%).

The third material tested was a mixture of sludge and microalgae with high humidity content, collected from a phytoremediation plant in Spain (FCC Aqualia S.A.). Fresh material has been sparged in 2 cm high layers in crystallizers, and then put in the oven at 100°C for 12 hours. Subsequently the dried material has been shredded using a professional shredder, making the grain size as uniform as possible. The starting materials here presented are showed in Figure 1.

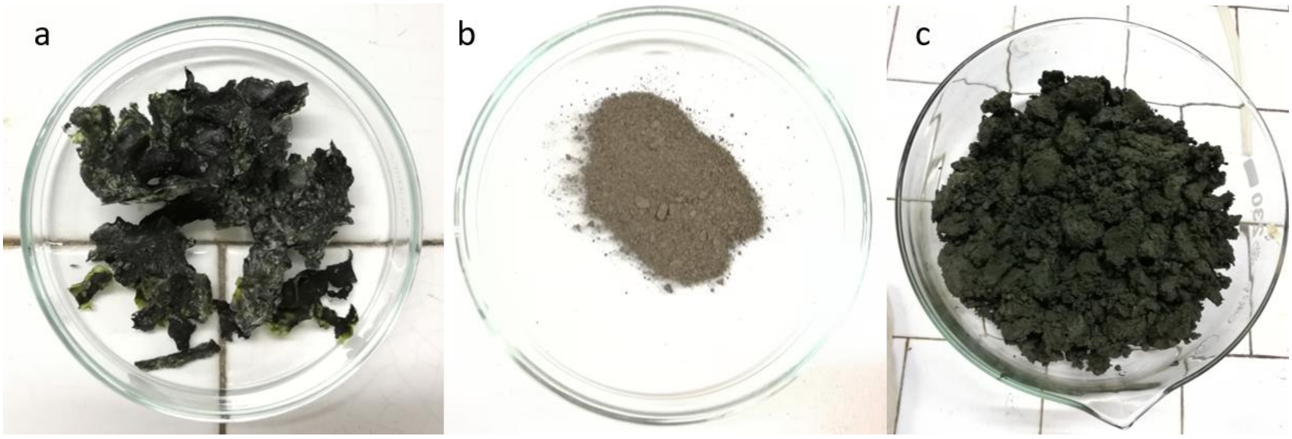

Figure 1 – Starting materials operated in the experimentation. (a) microalgae *Chlorella* cultivated in laboratory; b) dried sludge collected from municipal sewage sludge treatment plant; c) mixture of microalgae and sludge from the phytoremediation plant.

2.2 Oil extraction from microalgae

To achieve better yields in biochar recovery, oil extraction from microalgae using solvents has been operated as reported in Kumar et al. (2018) as control using a chloroform-methanol ratio 2:1. For the two samples containing algae, 1 g of dried sample has been immersed in 20 mL of solvent solution in a flat-bottomed pyrex glass flask, and stirred with a magnetic stirrer for 25 minutes, then centrifuged for 20 mins at 4000 rpm. The liquid fraction has been filtrated to avoid solid presence in the bulk liquid, and finally evaporated in Rotovapor to remove the solvents and determine the weight of extracted oil.

2.3 Thermogravimetric analysis (TGA) and infrared spectroscopy (IR)

Initial materials such as sludge, a mixture of algae and deriving sludge from the Aqualia plant, and powdered algae were first subjected to a thermogravimetric analysis (25÷800 °C, heating speed 20 °C min^{-1}) in nitrogen in order to better identify the temperature at which the pyrolysis process begins, and later to a TGA in air, to determine the content of ashes and inorganic material. Both TGA in nitrogen and air were then carried out on the samples of solid residue deriving from the process of pyrolysis to verify the effective pyrolysation of the initial material, and for a comparison of the ash content. Subsequent thermogravimetric analysis in nitrogen were carried out on the residues of microalgae subjected to oil extraction with solvent, to compare such samples with untreated starting materials.

Infrared spectroscopy (IR) has been used to characterize starting materials and both liquid and solid residues from pyrolysis process, and to detect the presence of water in liquid samples.

2.4 Pyrolysis process and products recovery

Substrates operated in the present experiment have been pyrolyzed through thermostatic sand bath S-70 (FALC instruments). A flat-bottomed pyrex glass flask has been immersed inside the heating body, containing 20.00 g of sample, in adhesion to the bottom of the sand-bath. The condition of absence of oxygen was guaranteed by a continuous flow of nitrogen regulated by a flow meter, blown directly inside the reactor. A three-way glass fitting was connected using a silicone tube, with a solvent trap containing acetone, immersed in crushed ice, used for the recovery of the oily fraction. The gases generated by the pyrolysis process pass through a silicone tube, they enter the trap where they are condensed. The experimentation was conducted at a temperature of 500 °C and 350 °C. For the samples subjected to the temperature of 500 °C the oven is kept at maximum operating temperature, and the temperature trend comes monitored by using a thermocouple inserted in the sand bath. Once the preset temperature was reached, it was kept constant for 30 minutes followed by switching off the heating device. As for the remaining samples, the use of a thermocouple allowed to monitor the temperature until it reaches 350 °C. This value was kept for about 30 minutes by acting on the thermoregulator of the oven itself. After this period, the device switched off. After cooling of the glass components, it was possible to recover the pyrolysis solid and liquid products. All experiments have been conducted in triplicates. Table 1 summarizes the samples analysed throughout the experimentation.

Table 1 – Samples summary. Each sample has been tested in triplicates.

Sample ID	Substrate	Temperature

1	Microalgae *Chlorella*	500 °C
2	Microalgae *Chlorella*	350 °C
3	Sludge from WWTP	500 °C
4	Sludge from WWTP	350 °C
5	Mix A+S	500 °C
6	Mix A+S	350 °C

Both solid (biochar) and liquid (bio-oil) fractions were recovered throughout the experiment. Gas fraction hasn't been recovered as retained not necessary for the present work, but estimated by difference. After pyrolysis process, all glass components and silicon tubes have been washed with acetone to remove all solid and oil particles from the instrument. From this washing process a mixture of biochar, bio-oil, acetone and, eventually, water is obtained, subjected to further treatment to achieve separation of the components. To separate solid fraction, filtration using funnel Buchner was operated. Every filter has been weighed before and after filtration to determine the fraction successfully separated. Liquid fraction (a mixture of acetone and oil) was transferred in a balloon up to ¾ of volume, and then subjected to vacuum evaporation using Rotavapor R-100 (BUCHI) to remove the solvent. The balloon has been weighed before and after use. If water was detected in the sample during IR analysis, anhydrous Na_2SO_4 was added to the solution, that was then filtrated and evaporated.

Percentages of biochar and bio-oil successfully recovered have been calculated as it follows (Eq. (1) and (2), respectively):

$$\% \, biochar = \frac{W_{biochar}}{W_i - W_{H_2O}} \cdot 100 \qquad (1)$$

where $W_{biochar}$ is the weight of biochar resulting from the test, W_i is the initial weight of the sample (20 g for each test) and W_{H_2O} is the weight of water present in the initial sample, deduced from the TGA analysis.

$$\% \, bio-oil = \frac{W_{bio-oil}}{W_i - W_{H_2O}} \cdot 100 \qquad (2)$$

where $W_{bio\text{-}oil}$ is the weight of bio-oil resulting from the test, W_i is the initial weight of the sample (20 g for each test) and W_{H_2O} is the weight of water present in the initial sample, deduced from the TGA analysis.

3. Results

3.1 Starting material characterization

Each starting material has been characterized by performing TGA analysis in air (oxidative environment, reproducing the combustion process) and nitrogen (inert environment). In oxidative environment it is possible to evaluate the ashes content of the analysed material. TGA in inert environment was necessary to determine the pyrolysis temperature range suitable to the samples under examination. The thermochemical process in absence of oxygen leads to degradation of the volatile substances in the sample, leaving char as residue. Results of the TGA in air and nitrogen are summarized in Table 2.

Based on the percentage of ashes obtained from the TGA analysis, it has been estimated the percentage of microalgae and sludge in the sample from the real phytoremediation plant, corresponding to 15% and 85%, respectively. The ashes content in WWTP sludge sample is higher (30.2 ± 1.8%) than the ones containing microalgae, meaning that adding a small amount (15%) of microalgae in the mixture positively contributes in reducing the amount of ashes produced by the process, improving its quality. As for the TGA in nitrogen, is relevant to see how the residues of the process for the sludge-microalgae mixture, composed by char and inorganic residues, is higher than that produced by the single matrix itself, theoretically leading to an increased solid material recovery.

Table 2 – Amount of ashes (%) for the three samples based on TGA in air and nitrogen results.

Substrate	% ashes (800 °C)	% residues (char+ashes, 800 °C)
Microalgae *Chlorella*	13.7 ± 2.6	25.1 ± 1.4
Sludge WWTP	30.2 ± 1.8	36.2 ± 2.1
Mix A+S	24.4 ± 3.1	38.7 ± 1.9

3.2 Biochar production and characterization

Pyrolysis tests have been conducted under two different temperatures, at 350°C and 500°C. The resulting pyrolysis products are solid residue (biochar) and liquid residue (bio-oil). After cleaning the components with acetone, to remove solid residues and liquid particles, and separating the fractions, the biochar has been weighed directly.

Figure 2 represents the products obtained from the pyrolysis of the samples previously described. For all matrix examined, pyrolysis at 350 °C produces the more relevant amount of solid residue (biochar), while higher temperatures (500 °C) are generally better performing in the production of bio-oil. When considering only the broad production of biochar, WWTP sludge pyrolyzed at 350 °C is the better performing (82.0 ± 4.4 %) along with the mixture solid residue at the same temperature (82.7 ± 2.1%). As for liquid residues, higher temperatures are usually reported to be better performing than the ones operated in the present work (Atabani et al., 2013), but it can be stated that all samples pyrolyzed at 500 °C produced 13±3% of bio-oil.

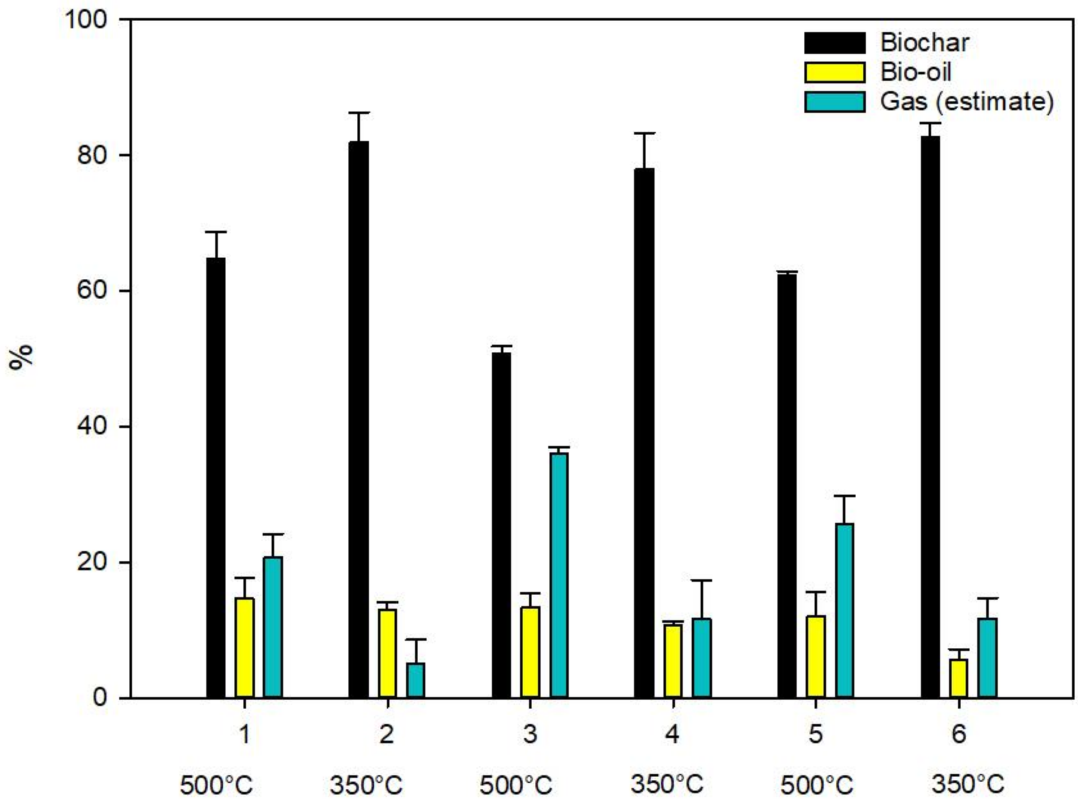

Figure 2 – Pyrolysis products: biochar (black), bio-oil (yellow) and gas (light blue, estimated). Error bars represent variability of results between triplicates.

In the present work, only the solid residue has been fully characterized. Biochar samples obtained from pyrolysis tests have been characterized through TGA, IR analysis and HHV (High Heating Value, UNI EN 14918:2010). By visual analysis, all samples appeared different from one sample to the other as function of temperature and starting material. Sample 2 and 4 from pyrolysis process at 350 °C (Figure 3 e, f) presented a fairer colour (brown) if compared to all the other samples (black). In microalgae biochar samples 1 and 2 (Figure 3 a, d, respectively) no colour differences were detectable, but they differed in consistence: sample 2 (Figure 3 d) was dusty, while sample 1 was in solid state (Figure 3 a). TGA in air was performed to evaluate the ashes content of the biochar, while TGA in nitrogen was used to evaluate the efficiency of the pyrolysis process, assessing the supplemental weight loss for each sample. Results obtained from the analysis are reported in Table 3.

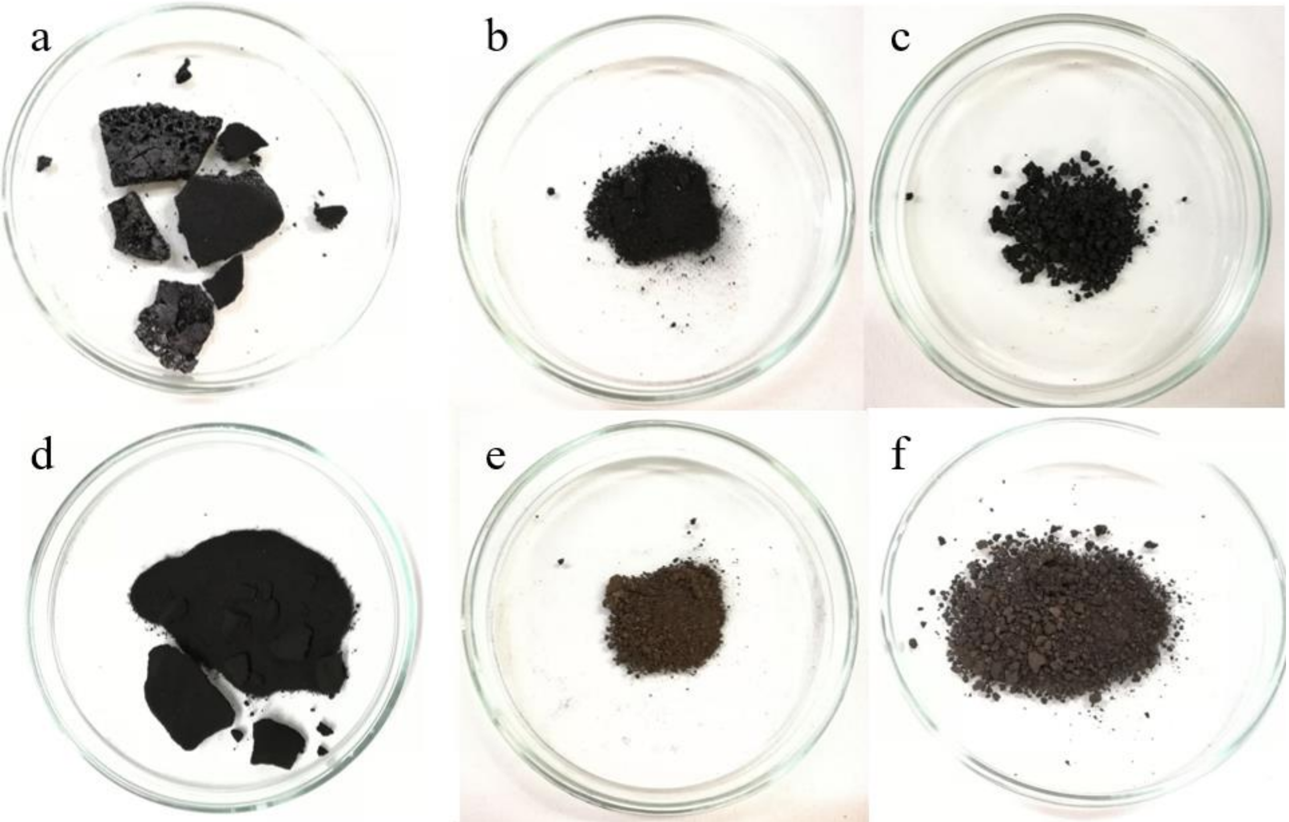

Figure 3 – Samples from pyrolysis at 500 °C: a) microalgae *Chlorella*; b) sludge from WWTP; c) Mix M+S. Samples from pyrolysis at 350 °C: d) microalgae *Chlorella*; e) sludge from WWTP; f) Mix M+S

IR analysis was performed before and after pyrolysis to evaluate the variation of bonds composing the materials due to the process.

Infrared analysis makes it possible to determine the functional groups and bonds present in the material. Therefore, the most interesting areas are the wavelength representing water and the carboxyl groups present in the mixture (between 3600 and 2500 cm^{-1}), the C-C and C-H bonds wavelength (3300 cm^{-1}); esters and fatty acids (1700 cm^{-1}), and Si-O bonds present in the inorganic material (1100 cm^{-1}). By comparing the different spectrums, all samples analysed before pyrolysis are very similar to each other, although the relationships between the various components change. Instead, the pyrolyzed sample (only represented by one sample in the graph), shows the obvious removal of water and organic acids due to pyrolysis, and the reduction of many of the functional groups present. Obviously, the Si-O bonds are preserved as not involved in pyrolysis. This corresponds to formation of a compound with a high carbon content, even if they are present still C-C and C-H bonds.

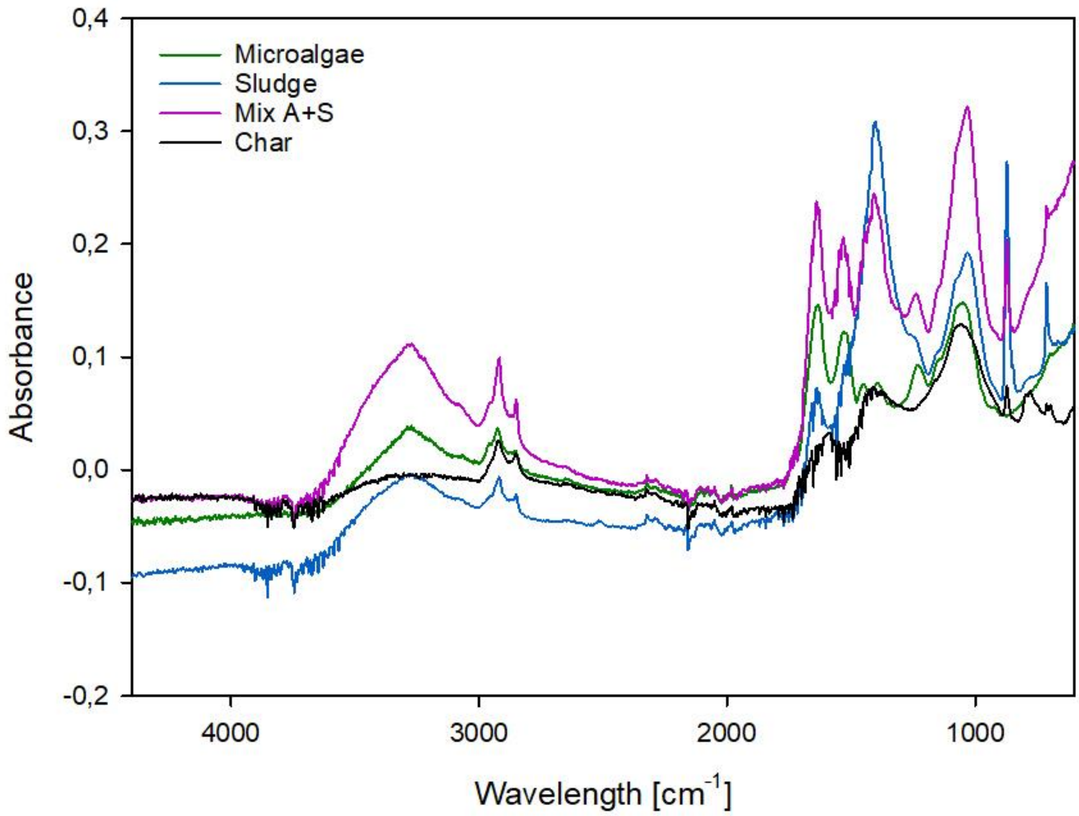

Figure 4 – IR analysis results. Absorbance curves for all the starting materials have been reported, while only the solid residue (biochar) from Mix A+S at 350 °C has been printed.

HHV analysis shows that the biochar produced by microalgae has a higher heating value (sample 1 and 2), which decreases with decreasing pyrolysis temperature. As for the HHV of the remaining samples, the result is less satisfactory, and this may suggest not to choose the combustion as the main application (Table 3).

Table 3 – Amount of ashes detected by TGA in air, weight loss (incomplete pyrolysis) from TGA analysis in nitrogen, and HHV value of biochar obtained by the samples analysed (1-6).

Sample	Pyrolysis temperature [°C]	Ashes [%]	Weight loss [%]	HHV [kJ kg^{-1}]
1	500	41.6 ± 2.3	16.8 [250-800 °C]	29091

2	350	31.5 ± 1.7	67.5 [250-800 °C]	26951
3	500	50.1 ± 2.2	23.9 [200-800 °C]	16629
4	350	37.0 ± 1.9	28.5 [250-600 °C] 17.7 [600-800 °C]	15648
5	500	44.3 ± 2.7	7.9 [500-600 °C] 18.9 [600-800 °C]	16245
6	350	34.5 ± 3.0	49.3 [250 – 800 °C]	16671

Oil extraction from microalgae by solvent has been conducted in order to verify whether this treatment increased the production yield of biochar. To verify the effect of the pretreatment, the sample of residue resulting from the extraction process has been subjected to TGA in nitrogen, and then the result has been compared to the results achieved on the raw material.
The sample of microalgae showed significant results, if compared to the initial sample. The yield in terms of biochar production increased from 25% to 33%. However, the mixture of microalgae and sludges didn’t show any benefit from the pretreatment (38% of biochar was produced in both cases).

4. Discussion

This work aimed to verify if coupling sewage sludge and microalgae in the pyrolysis process would be advantageous in terms of biochar production, as the sludge disposal problem is of major concern nowadays. The analysis of the products operated didn’t limit itself at observing the weight obtained for each matrix, but also went thorough to determine the percentage of ashes present in the final product, evaluating its quality. Different alternatives for coupling the two matrix together can be operated: an option could be the separate cultivation of microalgae added to the sludge directly at the time of pyrolysis, however, this strategy would be of little benefit if compared to the use of microalgae already in the wastewater treatment chain. This type of process, in addition to allow the removal of the nutrients present in the wastewater by the microalgae, produces a mixed biomass (sludge and microalgae), which once pyrolyzed produces a solid residue with excellent characteristics, as herein reported.

4.1 Possible applications of biochar

Pyrolysis process conditions (temperature, speed of heating, type of biomass, etc.) are highly important to determine the end use of biochar, since they directly contribute to develop different intrinsic characteristics of the solid residue (Hossain et al., 2011). It is therefore important to analyze the starting material before the process, in order to establish which is the best performing use for the biochar that will be obtained at the end of the process. Given the results obtained from HHV analysis on biochar samples, if compared with the HHV of the hard coal that is around 30 MJ / kg, it is it is evident that biochar can also be used as a fuel. However, the use alternatives are known, a more interesting solution could be the use of biochar in agriculture as an adsorbent of pollutants, and secondly the combustion of this residue, in order to exploit its energy capacity.

The most interesting outcomes for this product are mostly related to a possible re-use and valorisation of the product, from the perspective of a circular economy. An appealing use of the solid residue of pyrolysis is in agriculture as soil improver, allowing to increase crop productivity, but also to reduce soil pollution (Arthur et al. 2015). The biochar itself has an excellent adsorbent capacity for organic and inorganic pollutants, and is also able to reduce the CO_2 in the atmosphere. For agricultural use the carbon content in biochar must be greater than 50% of the dry mass, the quantity of N and P should be between 1 and 45%, and the pH should not exceed 10. The specific surface should also be greater than 150 m^2g^{-1} (Santos and Pires, 2018). The effects of biochar on the physical-chemical characteristics of the soils depend strongly on the characteristics of the soil itself and of the biomasses used for the production of solid residue (Obia et al., 2016).

A recent study from Oliveira et al. (2017) stated that the low temperatures of pyrolysis (<500 °C), favour the partial carbonization, producing biochar with small pores, reduced surface area and high groups functional containing oxygen. These characteristics make biochar suitable for the removal of inorganic pollutants. On the contrary, a biochar produced at high temperatures (> 500 °C), could be applied for the removal of organic pollutants, due to the higher surface area, making it suitable for environmental bioremediation. Another interesting prospect for this solid residue could be in the wastewater treatment field, specifically for the removal of toxic compounds released by industries, or instead of the granular activated carbon in WWTP facilities (Ahmed et al. 2014). Finally, due to its carbon-rich properties, biochar could be suitable for use as electrode in bioelectrochemical systems (BES) Normally, the material used at the anode is granular graphite or activated carbon, both expensive, therefore the use of biochar would be an excellent advantage also in economic terms (Callegari and Capodaglio, 2018).

Conclusions

This work aimed to verify if coupling sewage sludge and microalgae in the pyrolysis process would be advantageous in terms of biochar production, as the sludge disposal problem is of major concern nowadays. Products analysis herein operated wasn't limited at observing the weight obtained for each matrix, but also went through to determine the percentage of ashes present in the final product, helping in evaluation of its quality. Experimental data showed that, the slow pyrolysis at a temperature of 350 °C of a mixture of sludge and microalgae, in percentages of 85 and 15%, respectively, allowed to obtain 80% biochar by weight of the initial sample, of which only 24% were ashes. Comparing this result to the data deriving from the pyrolysis of WWTP sludge at the same temperature, where the amount of biochar was 74% of the initial weight, but containing 30% ashes, the co-pyrolysis of sewage sludge and microalgae allowed to obtain a more valuable product with multiple uses. Moreover, it contributes to reduce the problem of disposal of waste deriving from wastewater treatment. In terms of circular economy, biochar is a valuable compound recovered from disposal material such as WWTP sludge, with multiple interesting outcomes to be further evaluated.

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