

Evaluation of slow pyrolysis of kitchen and garden biowaste to produce biochar – Experimental study

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Abstract

Biowaste, which includes food and garden waste, represents a significant part of municipal waste. The present work aimed to determine the properties of three types of households biowaste and the possibility of using them as feedstock in slow pyrolysis to obtain biochar, as well as to determine the characteristics of the biochar obtained. The slow pyrolysis process of the biowaste was carried out in an electrically heated Horizontal Tube Furnace (HTF) at temperatures of 400°C, 500°C and 600°C under a nitrogen atmosphere. The properties of kitchen and garden biowaste differed significantly. In addition, the properties of the tested kitchen biowaste proved to be similar to those of other food wastes tested in other regions of the world, and to those of biomass feedstocks used in slow pyrolysis processes. For all biowaste studies, it was shown that as the pyrolysis temperature increases, the biochar yield decreases. Compared to biowaste before pyrolysis, biochar obtained from kitchen biowaste had a high carbon content, fixed carbon and higher HHV, while biochar obtained from garden biowaste had a lower carbon content and lower HHV.

Keywords: biowaste, household waste, food waste, garden waste, slow pyrolysis, biochar

1. Introduction

The constant increase in the amount of waste generated by society is creating an urgent need to develop new and better methods for its treatment. In the European Union, biowaste generation ranges from 118 to 138 million tons per year, with more than two-thirds of that being municipal biowaste and the remainder coming from the food industry [1].

In compliance with the Waste Framework Directive biowaste has been defined as "biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants" [2]. Based on this description, there are two major fractions that may be distinguished: the first is garden and park waste, and the second is food and kitchen waste [3]. Therefore, household biowaste can be considered a mixture of kitchen and garden waste [4].

In line with the circular economy, biowaste can be treated as a source of valuable resources such as

nutrients, organic matter and energy [5]. Despite the enormous recycling potential of this organic material, most of the biowaste produced each year in Europe is still lost through landfilling and incineration [6].

Up to now, the treatment of biowaste has been studied using biological and thermochemical processes [7]. Currently, two biological treatment methods for biowaste are most used: composting (treatment in the presence of oxygen) and anaerobic digestion (treatment in the absence of oxygen) [8].

The preferred treatment technique depends on the composition of the biowaste and the characteristics of the separate collection system. Separation of biowaste at source is an essential prerequisite for high-quality products [4]. Biowaste that is not collected separately and is part of municipal solid waste (MSW) is usually incinerated [5].

Due to the high moisture content of biowaste (> 60%) [9], thermochemical processing such as pyrolysis or gasification was less popular for biowaste treatment. Before thermochemical treatment, the biowaste must be dried, which consumes a lot of energy [7]. However, pyrolysis of biowaste is an efficient and sustainable way to create large amounts of renewable bioenergy, such as biochar and bio-oil while reducing greenhouse gas emissions and additional pollutants [10]. The main advantage of the pyrolysis process is that it allows the conversion of low-energy-density materials into high-energy-density biofuels [8].

Special consideration should be given to biochar, which is a stable, porous carbon-rich substance [11]. It is produced by pyrolysis of biomass at a low heating rate and relatively low temperature (400-700°C) [12]. Biochar can be used in a wide range of applications. The use of biochar for soil improvement [13] and water treatment has been most studied [14]. It can also be used as a fuel [15] or energy storage material [16]. Additionally, the use of biochar made from organic waste has implications for mitigating greenhouse gas emissions [17], climate change, and can contribute to carbon sequestration [13], [14].

This report focuses on kitchen (food) and garden biowaste (collected in spring and autumn) from Polish households and the potential to produce biochar from this biowaste using slow pyrolysis technology.

The main objectives of this work include:

- determination of the characteristics of the studied biowaste,
- determination of the effect of the temperature at which the slow pyrolysis process was carried out on the yield and physicochemical properties of the biochar obtained,
- determination of the characteristics of the obtained biochar.

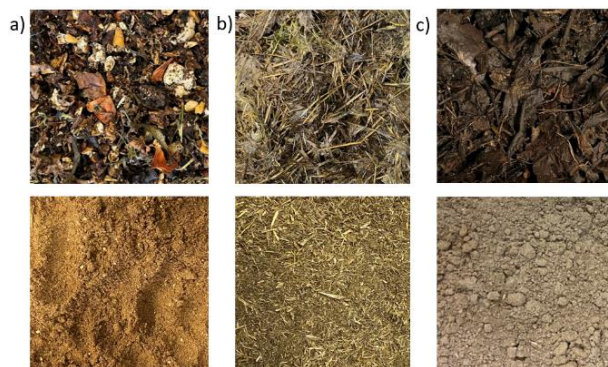


Figure 1. Biowaste before drying and after grinding
a) kitchen, b) spring garden, c) autumn garden.

2. Materials and methods

2.1. Biowaste samples

The biomass residues used in this work were three different types of biowaste collected in the Silesia region of Poland (Figure 1).

2.1.1. Kitchen biowaste

The first type was kitchen biowaste, which was collected in the summer in blocks of flats. Kitchen biowaste is organic waste that results from the preparation of meals by a single household living in a flat. The main components of this biowaste are vegetable and fruit waste (such as their inedible parts, peelings, seeds, etc.), bread and bakery products, pasta, rice, groats, meat, milk and dairy products, ready meals that have not been eaten, eggshells, coffee grounds, tea leaves, nut shells

2.1.2. Spring garden biowaste

The second type of biomass residue tested was garden biowaste collected from single-family houses in spring. The main component of this biowaste is grass, as gardening work is carried out during the spring period, mainly cutting grass and planting flowers and other plants. On the other hand, there may also have been partial amounts of kitchen waste among this biowaste. This is because, in single-family housing buildings, kitchen and garden biowaste are collected in one container

2.1.3. Autumn garden biowaste

The third type of biomass residue tested was garden biowaste collected from single-family houses in autumn. The main components of this biowaste are leaves and small twigs, as cleaning work is carried out in the garden during the autumn period, mainly raking leaves (among which there are also small twigs). In addition, there may also be other withered plants and cut grass. As with spring garden biowaste, there may also have been partial amounts of kitchen waste among this biowaste, because, in single-family housing buildings, kitchen and garden biowaste are collected in one container.

2.2. Characterization of the biowaste samples

The biowaste samples after collection (on a wet basis) were used to determine the total moisture content. Next, the prepared samples were completely dried in a laboratory dryer at 105°C for 24 h. After drying, the biowastes were ground in an IKA-WERKE M20 mill, which is used for dry grinding hard and friable substances.

2.2.1. Proximate analysis

The proximate analysis includes the determination of the moisture, volatile matter, fixed carbon and ash content of the biowaste.

Wet biowaste samples were used to determine the total moisture content and the measurement was carried out according to standard PN-EN ISO 18134-1:2023-02 [18]. The method consists of drying a biowaste sample at 105°C. The other determinations were carried out on dry samples. The determination of the volatile matter content was conducted in accordance with the standard PN-EN ISO 18123:2016-01 [19]. The method consists in burning a biowaste sample at 850°C under anaerobic conditions for 3 minutes. The determination of ash content in biowaste samples was carried out in accordance with standard PN-Z-15008-03 [20]. The method involves the calcination of a biowaste sample to a constant mass at a temperature of $815 \pm 10^\circ\text{C}$. Fixed carbon is the material remaining after determining the moisture, volatile matter and ash content [21]. Its content in the studied biowaste was calculated based on the formulas found in [11], [22].

2.2.2. Ultimate analysis

The ultimate analysis includes the determination of the elemental content of biowaste, that is, carbon, hydrogen, oxygen, nitrogen, sulphur, and chlorine. All determinations were carried out on dry samples. The determination of carbon and hydrogen content of the test samples was conducted in accordance with the standard ISO 609:1996 [23]. The method of determination consists of the combustion of a biowaste sample at 950°C in the presence of oxygen. Determination of total nitrogen in biowaste samples was carried out using the Kjeldahl method with pre-mineralization of the sample in concentrated H_2SO_4 in accordance with PN-G/-04523 [24]. The determination of the total sulphur content of the biowaste samples was conducted in accordance with the standard PN-ISO351/1999 [25]. The method involves combustion of the biowaste sample at 950°C in the presence of oxygen. The determination of the chlorine content of the biowaste samples was carried out in accordance with the standard PN-ISO 587:2000 [26]. The method consists of the combustion of a biowaste sample, which is in direct contact with an Eschka mixture, at 675°C in an oxidizing atmosphere. The oxygen content of the biowaste samples was determined by difference. In the expression of the ultimate analysis, the sum of the percentages of moisture, ash, carbon, hydrogen, nitrogen, sulphur and chlorine was subtracted from 100% [21].

2.2.3. Other biowaste properties

To further characterize the tested biowaste samples, the higher heating value (HHV) and lower heating value (LHV) were additionally determined in a calorimetric bomb [27] according to PN-ISO 1928:2020-05 [28]. In addition, according to the instructions in [29], the total

organic matter content, total organic carbon content and pH of the water extract of the biowaste samples were additionally determined. In addition, a surface analysis of the studied biowaste was performed using scanning electron microscopy (SEM) (JEOL, model JSM-7001F) [30].

2.3. Slow pyrolysis of biowaste

The slow pyrolysis process was carried out on a laboratory batch scale. An electrically heated horizontal tube furnace (HTF) with a water-cooled vessel from the Portuguese company Termolab-fornos Eléctricos Lda. was used (Figure 2). The unit operates at a maximum temperature of 1300°C. The wall temperature is continuously monitored using an S-type thermocouple. Inside the furnace is a horizontal tube with an internal diameter of 4 cm and a length of 55 cm made of recrystallised alumina. Inside this tube, the atmosphere of the slow pyrolysis process can be controlled. Two ceramic crucibles were placed inside the HTF, each containing a sample of approximately 2.5 g. The slow pyrolysis processes were carried out at 400°C, 500°C and 600°C, with a heating rate of 33°C/min and an inert atmosphere (nitrogen), with a residence time of 1 h and a nitrogen flow rate of 2 l/min.

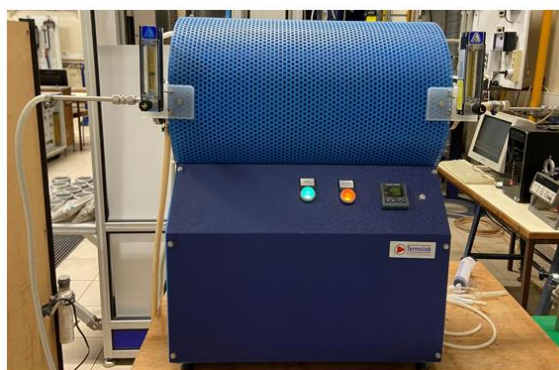


Figure 2. Horizontal Tube Furnace (HTF) used for the slow pyrolysis process.

2.4. Characterization of the biochar

To characterize the biochar obtained by slow pyrolysis, the proximate analysis, ultimate analysis and determination of higher and lower heating values were carried out. In addition, the surface of the obtained biochar was analyzed using a scanning electron microscope (SEM). All determinations were performed on dry samples and according to the standards presented in subsection 2.2 on biowaste characterization. It was assumed that the biochar was completely dried after pyrolysis, so the moisture content was not determined.

3. Results and discussion

3.1. Properties of the biowaste

The properties of the tested biowaste are summarized in Table 1.

Table 1. Properties of the tested biowastes.

biowaste	kitchen	spring garden	autumn garden
proximate analysis (% wt.) (dry basis)			
MC (total moisture content) (% wt.) (wet basis)	68.10	81.53	63.51
VM (volatile matter content)	76.55	42.43	43.75
A (ash content)	6.81	17.75	43.83
FC (fixed carbon)*	16.64	39.82	12.43
ultimate analysis (% wt.) (dry basis)			
C (carbon content)	43.36	31.94	29.99
H (hydrogen content)	7.03	4.53	4.02
N (nitrogen content)	3.12	2.84	1.19
S (sulphur content)	0.10	0.07	0.03
O (oxygen content)*	38.87	42.82	20.92
Cl (chlorine content)	0.71	0.05	0.01
H/C atomic ratio	1.93	1.69	1.60
O/C atomic ratio	0.67	1.01	0.52
other measurements (dry basis)			
HHV (higher heating value), MJ/kg	17.24	10.60	11.16
LHV (lower heating value), MJ/kg	15.69	9.60	10.27
CC (combustible compounds) (%wt.)	93.19	82.25	56.17
OS (total organic matter content) (%wt.)	90.06	81.77	55.32
MS (total mineral substances content) (%wt.)	9.94	18.23	44.68
C _{org} (total organic carbon content) (%wt.)	37.47	35.29	23.18
pH – (wet basis)	5.18	9.20	8.62

* by difference

Moisture content

The high moisture content of the tested biowaste requires pre-drying before slow pyrolysis. The analyzed sample of kitchen biowaste has a lower moisture content (68.10%) compared to literature data according to which food waste can contain 80% [9], or even up to 92.36% [31]. This difference may be due to the different compositions of biowaste, e.g., food biowaste consisting of peelings, raw vegetables and fruits will have a higher moisture content than biowaste consisting of partially dried products such as bread, eggshells, pasta or rice.

Researchers have shown that garden waste contains 50-60% moisture [9], [32]. Spring garden biowaste contained as much as 81.53% moisture. This may be because the grass, which is the main component of this biowaste, was cut after the rain and contained more water. Another explanation is that this biowaste may contain food biowaste with high moisture content, such as vegetable peelings. The autumn garden biowaste analyzed contained 63.51% moisture, which is slightly higher than indicated by literature data [9], [32].

Volatile matter content

Of the samples analyzed, kitchen biowaste has the highest volatile matter content (76.55%). This result is slightly higher than the literature data according to which food waste contains around 71.00% [31], [33]. The content of volatile matter in

the analyzed spring and autumn garden biowaste is similar at 42.43% and 43.75%, respectively, while it is almost twice as low as the presented literature values for garden waste (84.50%) [32] and shredded green waste (77.60%) [34].

Ash content

The ash content of the tested kitchen biowaste (6.81%) was lower than for another kitchen biowaste, which contained approximately 10% of ash [31], [33]. Both garden biowaste studied contained significantly more ash than the literature data according to which this waste showed the lowest ash content of 1.00% [32], [34]. Spring garden biowaste contained 17.75% ash, while the ash content of lawn grass is 3.85% [35]. The ash content of autumn garden biowaste was as high as 43.83% and is more similar to the ash content of the municipal solid waste (MSW) organic fraction (44.30%) [36]. Such large differences in the ash content of both garden biowaste samples may indicate its contamination. Garden biowaste is collected from the ground, usually with a rake it is collected in one place and then manually or with a spatula it is put into a container. During the raking of grass or leaves, there is a risk of collecting soil, rocks or other contaminants, which will be the main inorganic component of the raw material [11]. For the garden biowaste analysed, it can be concluded that autumn biowaste was more contaminated than spring biowaste.

Fixed carbon content

The fixed carbon content of kitchen biowaste (16.64%) and autumn garden biowaste (12.43%) was similar to literature data according to which food waste shows 18.50% [31], [33] and garden waste 15.00% fixed carbon [32], [34]. In contrast, the fixed carbon content of spring garden biowaste (39.82%) was more than twice as high.

Carbon content

The carbon content of kitchen biowaste (43.36%) is comparable to literature data, according to which these biowastes contain 46.10% [33] or 41.70% [31] carbon. The carbon content of the spring and autumn garden biowaste tested is similar to each other at 31.94% and 29.99%, respectively, while it is much lower than that reported in the literature for garden waste at 50.12% [32] and for grass ranging from 42.85% [35] to 45.57% [37].

Hydrogen content

According to literature data, both kitchen and garden biowaste contain between 5.66% and 7.47% hydrogen [31], [33], [34], [35]. The hydrogen content of the tested kitchen biowaste is within the upper range reported by other

researchers. In contrast, the hydrogen content of both garden biowaste studied is lower than reported in the literature for garden waste. However, it is comparable to the hydrogen content obtained for the organic fraction of MSW (4.70%) [36].

Nitrogen content

The tested kitchen biowaste on a dry basis contained 3.12% nitrogen, which is comparable to the nitrogen content of the canteen food biowaste of 3.49% [31]. The nitrogen content of the dry spring garden and autumn garden biowaste was 2.84% and 1.19%. Both studied garden biowaste contain significantly more nitrogen than garden waste studied by other researchers, which contains between 0.14% [32] and 0.20% [34] of this component. The nitrogen content of the spring garden biowaste studied is 2.84% which is similar to the nitrogen content of lawn grass, equal to 2.68% [35].

Oxygen content

Comparing the oxygen content of the analysed kitchen biowaste (38.87%) with the oxygen content of the food biowaste studied by Rago et al. (37.09%) [31] and Chhabra et al. (36.55%) [33], it can be concluded that its content is similar. According to literature data, the oxygen content of garden biowaste ranges from 39.40% [38] to 45.91% [34]. The obtained oxygen content for spring garden biowaste (42.82%) was within the given range. On the other hand, the oxygen content of autumn garden biowaste (20.92%) was significantly lower than indicated in the literature. It is also lower than the oxygen content of the yard waste fraction of MSW, which is 26.39% [33].

Sulphur content

The sulphur content of kitchen, spring garden and autumn garden biowaste was 0.10%, 0.07% and 0.03%, respectively. This is significantly less than the sulphur content of the organic fraction of MSW, which is 0.40% [36]. Furthermore, the sulphur content of the two analysed garden biowastes is similar to the literature values, which for garden biowaste ranges from 0.03% [34] to 0.08% [32].

Chlorine content

The chlorine content of kitchen, spring garden and autumn garden biowaste was 0.71%, 0.05% and 0.01%, respectively. From the analysed biowaste, kitchen biowaste has the highest chlorine content. This may be because table salt, namely sodium chloride (NaCl), is added to food, which by weight consists of 60% chloride [39]. Both garden biowaste analysed contain significantly less chlorine than the content shown for grasses, which is 0.74% [37].

Higher heating value (HHV)

The higher heating value of the analysed kitchen biowaste was 17.24 MJ/kg. This is higher than the value of 15.08 MJ/kg obtained for the canteen food waste [31]. The higher heating value of the analysed spring and autumn garden biowaste was 10.60 MJ/kg and 11.16 MJ/kg, respectively. These values are significantly lower than the 18.12 MJ/kg obtained for shredded green waste [34].

Lower heating value (LHV)

The lower heating values of the analysed kitchen, spring garden and autumn garden biowaste on a dry basis were 15.69 MJ/kg, 9.60 MJ/kg and 10.27 MJ/kg, respectively. These values result from the higher heating value but are lower because it does not include the latent heat of water vapour condensation produced during the combustion process [21].

Other properties of biowaste

The combustible compounds content of kitchen, spring garden and autumn garden biowaste was 93.19%, 82.25% and 56.17%, respectively. This means that, compared to the tested biowaste, kitchen biowaste is the easiest to ignite and autumn garden biowaste is the most difficult to ignite.

The total organic matter content of kitchen, spring garden and autumn garden biowaste was 90.06%, 81.77% and 55.32%, respectively. This means that kitchen biowaste is the most degradable, while autumn garden biowaste is the least degradable. The total organic matter content of the biowaste will influence how the waste is collected and how it is stored [9].

The pH values of the tested kitchen, spring garden and autumn garden biowaste on a wet basis were 5.18, 9.20 and 8.62, respectively. This means that the kitchen biowaste has an acidic pH, while both garden biowaste has an alkaline pH.

SEM analysis

Analysis of SEM images of all tested biowastes confirmed its heterogeneous nature and that the studied biowastes are different from each other and consist of different types of particles (Figure 3). Some kitchen biowaste particles had a smooth surface and marked sharp edges, while the surface of other particles was rough or irregular and the edges were not visible. For spring biowaste, large, elongated particles with visible edges were typical, forming a porous structure inside these particles. This structure is characteristic of plants, including blades of grass.

Typical for autumn garden biowaste were relatively small particles with an irregular, rough surface with visible cavities.

Summary of properties of tested biowaste

Among the studied biowaste, kitchen biowaste contains the highest volatile matter (76.55%), carbon (43.36%) and hydrogen (7.03%) and the least ash (6.81%), which has a positive impact on biochar production through the slow pyrolysis process. In addition, its HHV value (17.24 MJ/kg) is also the highest. On the other hand, kitchen biowaste, of all tested, contains the highest amount of nitrogen (3.12%), chlorine (0.71%) and sulphur (0.10%) which can negatively affect NO_x, SO_x or HCl emissions. In addition, the chlorine and sulphur content can cause corrosion of the installation.

All the properties of the tested kitchen biowaste are similar to literature values obtained in different regions of the world for food waste [31], [33]. These results confirm the conclusions made by Ilakovac et al [40], who found that regardless of the country, the composition of food waste generated in households is the same.

Compared to the literature data of other garden wastes, the studied spring garden biowaste is characterised by higher contents of moisture (81.53%), ash (17.75%) and fixed carbon (39.82%) and lower contents of volatile matter (42.43%), carbon (31.94%), hydrogen (4.53%) and chlorine (0.05%). In contrast, the content of oxygen (42.82%), nitrogen (2.84%) and sulphur (0.07%) in spring garden biowaste is similar to literature data for garden waste. In addition, compared to the literature data, the spring garden biowaste has a lower higher heating value (10.60 MJ/kg).

In contrast, autumn garden biowaste has a higher moisture content (63.51%), nitrogen content (1.19%) and a much higher ash content (43.83%) compared to literature data. On the other hand, it has lower volatile matter (43.75%), carbon (29.99%), hydrogen (4.02%), oxygen (20.92%), chlorine (0.01%) and a lower HHV (11.16 MJ/kg). In addition, the fixed carbon (12.43%) and sulphur (0.03%) content is similar to literature data for garden waste

In addition, the obtained properties of the biowaste were compared with those of typical biomass materials used to produce biochar by pyrolysis, such as wood [15], almond shells [22] and rice

husks [41]. It was shown that among the biowaste analyzed, kitchen biowaste has the most similar properties and thus should be best suited as a feedstock for the production of biochar through the slow pyrolysis process.

3.2. Biochar yield from slow pyrolysis process

The mass yield of biochar (Y_m) from the slow pyrolysis of the analysed biowaste is shown in Table 2. By analysing these results, for all the biowaste studied, it can be concluded that as the pyrolysis temperature increases, the yield of biochar decreases. The same relationship for green waste was obtained by other researchers [42]. This is in accordance with theoretical knowledge, because at low temperatures carbonisation reactions take place, while at higher temperatures devolatilisation reactions take place releasing more volatiles, leading to an increase in bio-oil and gas yields, which were not investigated in this work [11].

Comparing all the biowaste analysed, the highest biochar yields at each pyrolysis temperature were obtained for autumn garden biowaste, while the lowest biochar yields were obtained for kitchen biowaste. However, it should be noted that the analysed autumn garden biowaste contained as much as 43.85% ash, the spring garden biowaste 17.75% and the kitchen biowaste 6.81%, which also affects the biochar yield on a dry basis, because the ash contained in the biowaste will also be present in the obtained biochar.

3.3. Properties of the biochar

The properties of the obtained biochars are summarized in Table 2. Of all the biochar analysed, kitchen biochar obtained at a pyrolysis temperature of 400°C showed the highest content of volatile matter (20.49%), carbon (58.02%), hydrogen (4.00%) and the highest HHV (22.68 MJ/kg). Furthermore, this biochar showed the lowest ash content (18.57%). These properties indicate that this biochar can be used as a fuel. On the other hand, the high nitrogen content (3.64%), which may cause increased NO_x emissions, may have a negative impact. In addition, the high content of combustible compounds (81.43%) may have a negative impact on the storage of such biochar, as there will be a risk of uncontrolled ignition. The yield of this biochar was 36.64% and was the highest obtained for a kitchen biochar. Furthermore, this yield was higher than the typical yield of biochar from a slow pyrolysis process, which according to the literature is 35% [22]. Biochar with such properties could be used as carbon sequestration or soil improvement through enhanced water and nutrient retention.

Table 2. Yield and properties of biochar obtained from slow pyrolysis of biowaste.

biochar	kitchen			spring garden			autumn garden		
	400°C	500°C	600°C	400°C	500°C	600°C	400°C	500°C	600°C
Y_m (mass yield of biochar), % wt. (dry basis)	36.64	32.02	28.71	66.53	58.13	60.07	66.99	63.15	60.68
proximate analysis (% wt.) (dry basis)									
VM (volatile matter content)	20.49	14.88	11.14	12.59	11.65	5.89	15.42	12.10	5.76
A (ash content)	18.57	21.81	21.09	64.69	65.38	72.57	61.71	64.38	71.32
FC (fixed carbon) *	60.94	63.31	67.77	22.73	22.96	21.54	22.87	23.52	22.93
ultimate analysis (% wt.) (dry basis)									
C (carbon content)	58.02	54.81	55.55	25.34	26.60	21.00	27.84	27.45	25.62
H (hydrogen content)	4.00	3.02	2.67	2.41	1.71	1.41	2.80	2.54	1.47
N (nitrogen content)	3.64	3.46	3.01	1.44	1.52	1.05	1.15	1.00	1.02
O (oxygen content) **	15.77	16.90	17.68	6.12	4.79	3.97	6.50	4.63	0.57
H/C atomic ratio	0.82	0.66	0.57	1.13	0.76	0.80	1.20	1.10	0.68
O/C atomic ratio	0.20	0.23	0.24	0.18	0.14	0.14	0.18	0.13	0.02
other measurements (dry basis)									
HHV (higher heating value), MJ/kg	22.68	20.84	21.90	9.04	8.95	7.51	9.96	9.02	8.40
LHV (lower heating value), MJ/kg	21.80	20.17	21.31	8.51	8.58	7.20	9.35	8.46	8.07
CC (combustible compounds), (% wt.)	81.43	78.19	78.91	35.31	34.62	27.43	38.29	35.62	28.68

* by difference

** by difference (without considering the sulphur and chlorine content)

Compared to kitchen biowaste before pyrolysis, kitchen biochar obtained at any pyrolysis temperature has a higher carbon content, fixed carbon and a higher HHV, which means that kitchen biowaste is a suitable feedstock to produce biochar by slow pyrolysis.

The properties of the obtained spring garden and autumn garden biochar were similar for the respective pyrolysis temperatures, whereas significantly different from those of the kitchen biochar.

The yield of both garden biochar, was almost twice as high as that of kitchen biochar. In addition, the garden biochar contained more than three times as much ash as the kitchen

biochar. This high ash content resulted in a lower volatile matter, carbon and hydrogen content than in the kitchen biochar. This also had an impact on HHV, which was at least twice as low compared to kitchen biochar.

Furthermore, the biochar contained less carbon and had a lower HHV compared to the spring and autumn garden biowaste before pyrolysis. As biochar should be carbon-rich and have a calorific value in the range of 20-36 MJ/kg [43], this means that the studied garden biowaste is not a suitable feedstock for biochar production by slow pyrolysis.

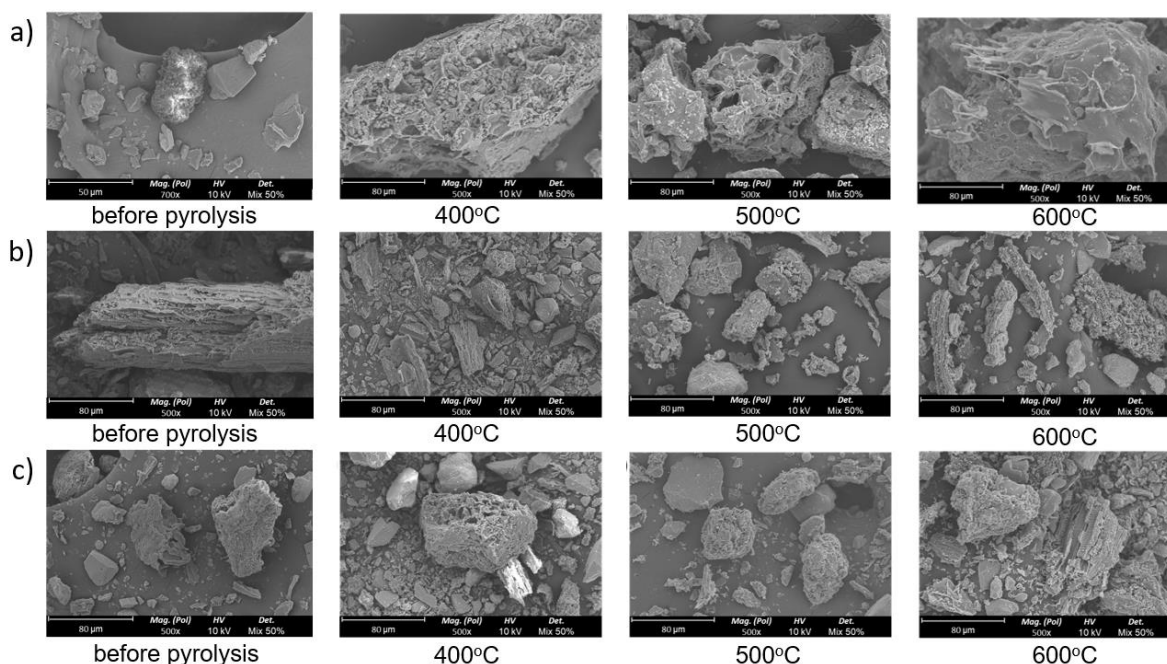


Figure 3. SEM images of: a) kitchen, b) spring garden, c) autumn garden biowaste before slow pyrolysis and biochar obtained from these biowastes at pyrolysis temperatures of 400°C, 500°C and 600°C.

On the other hand, knowing the composition of the ash contained in this biochar, it is possible to use it as a soil amendment to improve soil fertility. In contrast, it is possible that the studied garden biowaste was contaminated (with soil, rocks, etc.) during collection and this could have a negative impact on the properties of the obtained biochar. On the other hand, it is not known whether such contamination can be completely avoided as the garden biowaste is raked and collected directly from the ground.

Image analysis by scanning electron microscope (SEM) showed that all the tested biochar, as well as the biowaste from which it was formed, was heterogeneous and composed of particles of different shapes and sizes (Figure 3). As the pyrolysis temperature increases, the particles of the kitchen biochar become larger and more porous. Irrespective of the pyrolysis temperature, the particles of spring garden biochar were similar to each other and to the elongated porous structures present in the biowaste before pyrolysis. As the pyrolysis temperature increased, the particles of the autumn garden biochar were increasingly porous. At the same time, it is worth noting that the porous structure of both garden biochar was similar while it differed from the porous structure of kitchen biochar.

4. Conclusions

In the present work investigated the properties of three types of biowaste collected in Poland, being kitchen, spring garden and autumn garden biowaste. The next stage of the work was to determine the potential for biochar production from the studied biowaste using slow pyrolysis. This process was carried out in an electrically heated Horizontal Tube Furnace (HTF) in a nitrogen atmosphere at temperatures of 400°C, 500°C and 600°C. After that, the properties of the obtained biochar were studied.

The main conclusions of this work can be summarized as follows:

- All the biowaste tested had a high moisture content (between 63.51% and 81.53%), which means that the biowaste needs to be dried before the slow pyrolysis process.
- Analysis of properties and SEM images confirmed that the studied biowaste has heterogeneous nature and differ from each other therefore should be collected separately.
- The properties of the kitchen biowaste tested are comparable to those of food waste tested by other researchers in different regions of the world, and are similar to those of typical biomasses used to produce biochar by slow pyrolysis.

- Both garden biowaste tested may have been contaminated (soil, rocks) during collection, which affected the high ash content of spring (17.75%) and autumn (43.83%) biowaste. This, in turn affected all the properties of the garden biowaste which differed significantly from both literature data of other garden wastes and from the properties of typical biomass feedstocks used to produce biochar in the slow pyrolysis.
- For all the biowaste tested, it was shown that the biochar yield decreased with increasing pyrolysis temperature. The maximum mass yield of biochar for kitchen, spring garden and autumn garden biowaste was 36.64%, 66.53% and 66.99%, respectively.
- Kitchen biochar, compared to kitchen biowaste before pyrolysis, had higher carbon content, fixed carbon and higher HHV. In addition, SEM image analysis showed that as the temperature increases, the kitchen biochar particles become larger and more porous. Biochar with such properties can be used for carbon sequestration or soil improvement through increased water and nutrient retention.
- Both types of garden biochar contained less carbon and had a lower HHV than the garden biowaste from which it was produced. In addition, the garden biochar contained more than three times as much ash as the kitchen biochar.

Complementing these conclusions, future work should be developed in the direction of optimizing the slow pyrolysis process of kitchen biowaste to achieve higher biochar yields. In addition, specific applications of the biochar obtained from kitchen biowaste would need to be explored. It is necessary to conduct an economic analysis of the slow pyrolysis process of kitchen biowaste, because despite promising technological results, it may not be economically feasible to implement this project. In addition, due to the laboratory scale of the experiment carried out, it would be necessary to carry out the same experiment on a pilot or semi-industrial scale.

In the case of garden biowaste, it should be investigated whether there is a chance to avoid its contamination. In addition, due to the high yield and high ash content of biochar, the properties of the ash should be investigated, as the ash may contain nutrients that have a positive effect on plant growth, but may also have a negative effect on soil properties depending on the type of soil to which it is applied.

References

- [1] European Commission, Directorate-General for Environment, Dubois, M., Sims, E., Moerman, T., et al., Guidance for separate collection of municipal waste, Publications Office, 2020, <https://data.europa.eu/doi/10.2779/691513>
- [2] DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008L0098-20180705&from=EN> ; (date of access: 20.11.2022)
- [3] European Union. European Regional Development Fund. A Policy Brief from the Policy Learning Platform on Environment and resource efficiency The biowaste management challenge. (2021).
- [4] Pavlas, M., Dvořáček, J., Pitschke, T., & Peche, R. (n.d.). Biowaste Treatment and Waste-To-Energy-Environmental Benefits. <https://doi.org/10.3390/en13081994>
- [5] European Commission, 2008, Green Paper on the management of bio-waste in the European Union (COM(2008) 811 final).
- [6] Scherhafer, S., Moates, G., Hartikainen, H., Waldron, K., & Obersteiner, G. (2018). Environmental impacts of food waste in Europe. *Waste Management* (New York, N.Y.), 77, 98–113. <https://doi.org/10.1016/J.WASMAN.2018.04.038>
- [7] Bhakta Sharma, H., Panigrahi, S., & Dubey, B. K. (2021). Food waste hydrothermal carbonization: Study on the effects of reaction severities, pelletization and framework development using approaches of the circular economy. *Bioresource Technology*, 333. <https://doi.org/10.1016/j.biortech.2021.125187>
- [8] European Environment Agency. (2020). Bio-waste in Europe turning challenges into opportunities. No 04/2020. ISBN 978-92-9480-223-1; doi:10.2800/630938
- [9] Dubois, M., Sims, E., Moerman, T., Watson, D., Bauer, B., Bel, J.-B., Mehlhart, G., European Commission. Environment Directorate-General., European Economic Community., PlanMiljø., Association des cités et régions pour le recyclage et la gestion durable des ressources., RWA., & Öko-Institut. (2020.). Guidance for separate collection of municipal waste.
- [10] Awasthi, M. K., Sarsaiya, S., Wainaina, S., Rajendran, K., Awasthi, S. K., Liu, T., Duan, Y., Jain, A., Sindhu, R., Binod, P., Pandey, A., Zhang, Z., & Taherzadeh, M. J. (2021). Techno-economics and life-cycle assessment of biological and thermochemical treatment of bio-waste. *Renewable and Sustainable Energy Reviews*, 144. <https://doi.org/10.1016/J.RSER.2021.110837>
- [11] Basu, P. (2013). Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory. Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory. 1-530.
- [12] Tomczyk, A., Sokółowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. In *Reviews in Environmental Science and Biotechnology* (Vol. 19, Issue 1, pp. 191–215). Springer. <https://doi.org/10.1007/s11157-020-09523-3>
- [13] Haider, F. U., Coulter, J. A., Cai, L., Hussain, S., Cheema, S. A., Wu, J., Zhang, R. (2022). An overview on biochar production, its implications, and mechanisms of biochar-induced amelioration of soil and plant characteristics. *Pedosphere*, 32(1), 107–130. [https://doi.org/10.1016/S1002-0160\(20\)60094-7](https://doi.org/10.1016/S1002-0160(20)60094-7)
- [14] Panwar, N. L., Pawar, A., & Salvi, B. L. (2019). Comprehensive review on production and utilization of biochar. In *SN Applied Sciences* (Vol. 1, Issue 2). Springer Nature. <https://doi.org/10.1007/s42452-019-0172-6>
- [15] Amer, M., Elwardany, A. (2020). Biomass Carbonization. 10.5772/intechopen.90480
- [16] Liu, Y., Yang, X., Zhang, J., & Zhu, Z. (2022). Process Simulation of Preparing Biochar by Biomass Pyrolysis Via Aspen Plus and Its Economic Evaluation. *Waste and Biomass Valorization*, 13(5), 2609–2622. <https://doi.org/10.1007/s12649-021-01671-z>
- [17] Jeyasubramanian, K., Thangagiri, B., Sakthivel, A., Dhavethu Raja, J., Seenivasan, S., Vallinayagam, P., Madhavan, D., Malathi Devi, S., & Rathika, B. (2021). A complete review on biochar: Production, property, multifaceted applications, interaction mechanism and computational approach. *Fuel*, 292. <https://doi.org/10.1016/j.fuel.2021.120243>
- [18] PN-EN ISO 18134-1:2023-02. Biopaliwa stałe. Oznaczenie zawartości wilgoci. Część 1: Metoda referencyjna.
- [19] The Polish Committee for Standardization, Solid Biofuels. Determination of The Content of Volatile Matter; PN-EN ISO 18123:2016-01, Warszawa, Poland, 2018. (in Polish)
- [20] PN-Z-15008-03:1993. Odpady komunalne stałe. Badania właściwości paliwowych. Oznaczenie zawartości części palnych i niepalnych.
- [21] James G. Speight. Handbook of Coal Analysis: Chemical Analysis. John Wiley & Sons, Inc, 2005.
- [22] R. Chandraratne, M., G. Daful, A. (2022). Recent Advances in Thermochemical Conversion of Biomass. In *Recent Perspectives in Pyrolysis Research*. IntechOpen. <https://doi.org/10.5772/intechopen.100060>
- [23] ISO 609:1996. Solid mineral fuels - Determination of carbon and hydrogen - High temperature combustion method
- [24] PN-G-04523:1992. Paliwa stałe. Oznaczenie zawartości azotu metodą Kjeldahla.
- [25] PN-ISO351/1999 – Paliwa stałe – Oznaczenie zawartości Siarki - metodą spalania w wysokiej temperaturze
- [26] PN-ISO 587:2000. Paliwa stałe. Oznaczenie zawartości chloru z zastosowaniem mieszaniny Eschki.
- [27] Kotlicki, T. (2007). Oznaczenie ciepła spalania węgla za pomocą kalorymetru instrukcja do ćwiczenia laboratoryjnego
- [28] PN-ISO 1928:2020-05. Paliwa stałe. Oznaczenie ciepła spalania metodą spalania w bombie kalorymetrycznej i obliczanie wartości opałowej
- [29] Collective work edited by J. Biegańska, Metody analizy w gospodarce odpadami. Zbiór instrukcji do ćwiczeń laboratoryjnych. Wydawnictwo Politechniki Śląskiej, Gliwice 2008. (in Polish)

- [30] Zhou, W., Apkarian, R., Wang, Z.L., Joy, D. (2006). Fundamentals of Scanning Electron Microscopy (SEM). In: Zhou, W., Wang, Z.L. (eds) Scanning Microscopy for Nanotechnology. Springer, New York, NY. https://doi.org/10.1007/978-0-387-39620-0_1
- [31] Rago, Y. P., Surroop, D., & Mohee, R. (2018). Assessing the potential of biofuel (biochar) production from food wastes through thermal treatment. *Bioresource Technology*, 248, 258–264. <https://doi.org/10.1016/j.biortech.2017.06.108>
- [32] Safarian, S., Unnthorsson, R., & Richter, C. (2020). Simulation and Performance Analysis of Integrated Gasification-Syngas Fermentation Plant for Lignocellulosic Ethanol Production. *Fermentation*, 6(3). <https://doi.org/10.3390/fermentation6030068>
- [33] Chhabra, V., Bhattacharya, S., & Shastri, Y. (2019). Pyrolysis of mixed municipal solid waste: Characterisation, interaction effect and kinetic modelling using the thermogravimetric approach. *Waste Management*, 90, 152–167. <https://doi.org/10.1016/j.wasman.2019.03.048>
- [34] Ward, J., Rasul, M. G., & Bhuiya, M. M. K. (2014). Energy recovery from biomass by fast pyrolysis. *Procedia Engineering*, 90, 669–674. <https://doi.org/10.1016/j.proeng.2014.11.791>
- [35] Guo, S., Dong, X., Liu, K., Yu, H., & Zhu, C. (2015). Chemical, energetic, and structural characteristics of hydrothermal carbonization solid products for lawn grass. *BioResources*, 10(3), 4613–4625. <https://doi.org/10.15376/biores.10.3.4613-4625>
- [36] Yang, Y., Wang, J., Chong, K., Bridgwater, A. v. (2018). A techno-economic analysis of energy recovery from organic fraction of municipal solid waste (MSW) by an integrated intermediate pyrolysis and combined heat and power (CHP) plant. *Energy Conversion and Management*, 174, 406–416. <https://doi.org/10.1016/j.enconman.2018.08.033>
- [37] Obernberger, I., Brunner, T., Bärnthaler, G. (2006). Chemical properties of solid biofuels-significance and impact. *Biomass and Bioenergy*, No. 30, pp. 973–982.
- [38] Dhyani, V., & Bhaskar, T. (2018). A comprehensive review on the pyrolysis of lignocellulosic biomass. *Renewable Energy*, 129, 695–716. <https://doi.org/10.1016/j.renene.2017.04.035>
- [39] Oštarić, F., Kalit, S., Curik, I., Mikulec, N. (2023) Influence of Sodium and Potassium Chloride on Rennet Coagulation and Curd Firmness in Bovine Milk. *Foods*, 12(12):2293. <https://doi.org/10.3390/foods12122293>
- [40] Ilakovac, B., Voca, N., Pezo, L., Cerjak, M. Quantification and determination of household food waste and its relation to sociodemographic characteristics in Croatia. *Waste Manag.* 2020 Feb 1;102:231-240. doi: 10.1016/j.wasman.2019.10.042. Epub 2019 Nov 1. PMID: 31683079.
- [41] Hu, Q., Shao, J., Yang, H., Yao, D., Wang, X., & Chen, H. (2015). Effects of binders on the properties of bio-char pellets. *Applied Energy*, 157, 508–516. <https://doi.org/10.1016/j.apenergy.2015.05.019>
- [42] Ronsse, F., van Hecke, S., Dickinson, D., & Prins, W. (2013). Production and characterization of slow pyrolysis biochar: Influence of feedstock type and pyrolysis conditions. *GCB Bioenergy*, 5(2), 104–115. <https://doi.org/10.1111/gcbb.12018>
- [43] Lohri, C. R., Diener, S., Zabaleta, I., Mertenat, A., & Zurbrugg, C. (2017). Treatment technologies for urban solid biowaste to create value products: a review with focus on low- and middle-income settings. In *Reviews in Environmental Science and Biotechnology* (Vol. 16, Issue 1, pp. 81–130). Springer Netherlands. <https://doi.org/10.1007/s11157-017-9422-5>