

Article

The Influence of Drying Sewage Sludge with the Addition of Walnut Shells on Changes in the Parameters and Chemical Composition of the Mixture

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Abstract: One method of preparing sludge for management and use is solar drying. To intensify the drying process, natural lignocellulosic additives can be used to alter the structure of the sludge and accelerate water evaporation. Light, hard materials with low absorption capacity are best suited for this purpose, e.g., walnut shells, which are unused waste. The aim of the study was to determine the impact of the evaluation of walnut shells on the sludge drying process and to assess the impact of the drying process on the chemical, physical, and fuel properties of the additive. The moisture content, crushing strength, chemical composition, and physical and fuel properties of mixtures were determined. A small addition of walnut shells (25%) was found to accelerate the drying process even in winter and spring (up to 30 days) compared to sludge without additives. Walnut shells retain their chemical composition and strength despite unfavourable conditions and a chemically aggressive environment, indicating they may be reused. The mixture containing sewage sludge and walnut shells has a calorific value of 15.6 MJ/kg, which is similar to wood; it is also fully biodegradable and suitable as a fertiliser to improve soil structure, as it contains approx. 80–90% DM (including approx. 40% carbon, 3% nitrogen, and other elements, such as phosphorus and potassium.)

Keywords: sewage sludge; solar drying; walnut shells



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1. Introduction

Following Poland's accession to the European Union, the environmental legislation has been adapted to meet EU requirements. This also applies to the disposal of wastewater and the treatment, management, and use of sewage sludge [1–3]. The rules are laid down in new or revised legislation and other documents of the European Union and compatible Polish documents [4–7]. Those regulations have established requirements for conditions and methods of sludge use, assuming that sludge storage would be abandoned while increasing its amount used for agriculture, nature, and energy purposes [8–10].

Sewage sludge is a by-product of wastewater treatment [11]. It may prove a useful fertilising material for soil [12]. The composition of sewage sludge varies depending on such things as the type of wastewater treated, the method of treatment, or its processing [13,14]. Sewage sludge must be prepared appropriately before use for natural purposes or thermal disposal [15,16]. This is necessary mainly due to the high water content of sewage sludge, the varying heavy metal content, and the variable degree of sanitary risk [17–19].

Approximately 10 million tonnes of sewage sludge are produced annually in EU countries, and this figure is steadily rising, especially among the newest Member States.

According to estimates by Statistics Poland, as much as 1,012,000 tonnes of sewage sludge were generated in Poland in 2023 alone. One very common method of sewage sludge management is agricultural and natural use [20]. Using sludge as an energy source is also becoming increasingly important, with many European countries incinerating anywhere from 30 to 50%. Due to transport costs, sludge drying is becoming increasingly popular. This includes not only thermal drying but also solar drying, which is particularly useful in smaller wastewater treatment plants [21–23]. The latter is increasingly common in countries such as France, Turkey, Spain, and Croatia, where climatic conditions favour natural methods. While Poland's climatic conditions are not as favourable, several dozen facilities of this kind are in operation; research on the solar drying process is also increasingly widespread [24].

It is most cost-effective to dispose of sewage sludge at the site where it is generated. Sludge disposal costs are particularly significant for small facilities [25]. Further, municipalities can obtain large amounts of green matter from urban greenery as well as from straw left over from cereal cultivation, sawdust, woodchips, and ash [26]. When combined with sludge, the material creates mixtures that can be used for agricultural purposes [27] and especially for energy purposes, solving the so-called sludge problem in small wastewater treatment plants and offering an additional benefit in the form of energy obtained from biofuel, which is cheaper than conventional fuels (about three times the price difference compared to solid fuels).

Due to the high cost of drying sewage sludge using conventional methods, interest in alternative drying methods has increased [28]. Solar dryers in temperate climates, also in Poland, can be successfully used to dry sewage sludge from small and medium-sized wastewater treatment plants [20–30]. Solar sludge dryers that lack additional heating for use in autumn and spring typically store the dried sludge. Solar drying is most effective in summer; unfortunately, Poland's temperate climate makes it impossible to dry the same amount of sludge each season [31]. A crucial aspect of the system is ventilation, which assists in the evaporation of water from the sludge [32]. Moreover, using additional biocomponents can improve drying conditions during unfavourable periods to enhance the physical and chemical parameters of the biomixture, which can be used for energy and agricultural purposes [33]. There are known methods of producing biomass briquettes (e.g., from straw), which can be used to obtain biofuels from biomixtures containing sewage sludge [34]. Solar drying and sludge management technology, including energy sludge management, bring together the issues of waste management as well as its agricultural and energy use and is a vital contribution to the development of closed-loop management methods [35].

Biomass drying methods can be divided into conventional drying and solar drying. Conventional drying is the process of removing moisture from a material using an external heat source such as fuel gas, oil, coal, or other fuel [36]. Those sources are used for conventional drying since this processing type allows energy to be generated. Conventional drying is mainly carried out using specially designed dryers or other equipment. These enable the controlled heating of the mixture, air circulation around the material, and automated material flipping to ensure optimal drying conditions and to obtain the desired results, i.e., a mixture with the required technological parameters [37]. While using non-renewable fuels, which entails high operating costs and greenhouse gas emissions and requires complex facilities, conventional drying makes sludge drying less dependent on atmospheric conditions, providing greater efficiency due to precise temperature control. Conventional drying is mainly used in food and agricultural industries, as well as the broader industry [38].

Solar drying is the process of removing moisture from a material using solar energy as the main heat source. The solar energy is converted into heat, which is used to evaporate water from the material being dried [39]. Solar drying is highly dependent on atmospheric conditions, but it has some advantages that make it preferable in terms of environmental sustainability, ecological performance, and low greenhouse gas emissions. Additional

advantages of solar drying are that the energy source is free and readily available, and the drying facilities are structurally simple. The use of solar energy, called solar constant, which is a fraction of the total energy emitted by the sun [40], as a heat source to evaporate moisture from materials has been known for centuries. Moisture is dissipated as a result of the sunlight acting on the surface of the material, which has low operating costs. Sludge drying can be economically sound as long as it does not significantly increase the cost of wastewater treatment due to its energy intensity [41,42]. Since it exploits a renewable energy source that is free and accessible most of the time, solar drying reduces the use of conventional fuels. It also contributes to the sustainable use of energy, a crucial resource for many sectors, including food and chemical industries, agriculture, biomass processing, and wastewater treatment. In Poland, the sun provides nearly 1000 kWh of energy per square metre of flat surface per year, an amount that allows water to evaporate efficiently from materials being dried. Sludge solar drying makes it possible to increase the dry matter content of different types of sludge from 20 to 75% within 15 to 25 days, with energy consumption ranging from 29 to 44 kWh/Mg of evaporated water. In comparison, conventional drying uses 70–110 kWh/Mg of evaporated water [43]. Using air as an energy carrier in solar dryers enables simplified dryer construction and lower operating costs [44,45]. For proper operation, the biomass stored in the dryer should be mechanically raked to facilitate drying. In disk, drum, and fluidised bed dryers, water evaporates at temperatures above 100 °C; however, this process occurs at lower temperatures in solar dryers with the contribution of sunlight due to the so-called “greenhouse effect”. While a small portion of the sunlight is reflected off on the dryer’s surface, most of the sunlight reaches the sludge and heats it. From the point of view of both capital expenditure and subsequent operating costs, this is currently the cheapest way to reduce the weight and volume of waste. This inherently simple drying technology creates a stable dry residue weighing four times less than the input and with a neutral peat-like odour. Various natural additives can be used to improve water evaporation during sludge drying. Further, various types of straw, wood chips, chopped straw, or walnut shells can be used as structuring material.

It is estimated that the walnut cultivation area in Poland amounted to 2500 hectares in 2015. Approximately 7000 tonnes of fruit were harvested in 2015, with an average yield of 2.5 tonnes per hectare. Most plantations, indeed almost half of them, are located in the Podkarpackie Voivodeship. Flesh is estimated to account for 50% of the nut’s weight. Hence, a minimum of 3500 tonnes of shells (not including exported fruit) enter the market each year. In 2022, approximately 163,000 tonnes of walnuts were harvested in Europe. Walnut shells have many properties and are the subject of many studies [46]. They are most often used as fuel or as an abrasive for metalworking.

This study aimed to determine the effect of the amount of walnut shell additive on sewage sludge solar drying parameters and evaluate the effect of the drying process on the physical properties and chemical composition of the additive used.

It was assumed that using walnut shells with sewage sludge would affect the solar drying time of sewage sludge and the mechanical strength of walnut shells after drying sewage sludge biomixtures containing different proportions of them. The authors also assumed that the conditions during the sludge drying process would cause significant changes in the structure of the walnut shells, at the very least, causing the degradation of low-polymerised carbohydrate compounds and the breakdown of the shells. Hence, there was a need to investigate the chemical composition of the shells before and after the drying process.

The scope of the research included physical analyses of the mixture drying process as well as physical and chemical analyses of the resulting mixtures.

2. Materials and Methods

Biomixture solar drying was carried out in a $4 \times 2.5 \times 2$ m plastic tunnel (area: 10 m²; volume: ca. 20 m³) at Experimental Station Marcellin of the Poznań University of Life Sciences. The tunnel structure was covered with white PE 140 g/m² foil with a UV4 filter

and featured 6 tilting windows and a zipped door. The tunnel was equipped with three stations (thermally insulated) measuring $1.8 \times 0.8 \times 0.15$ m, with a capacity of 216 dm^3 each (Figure 1).

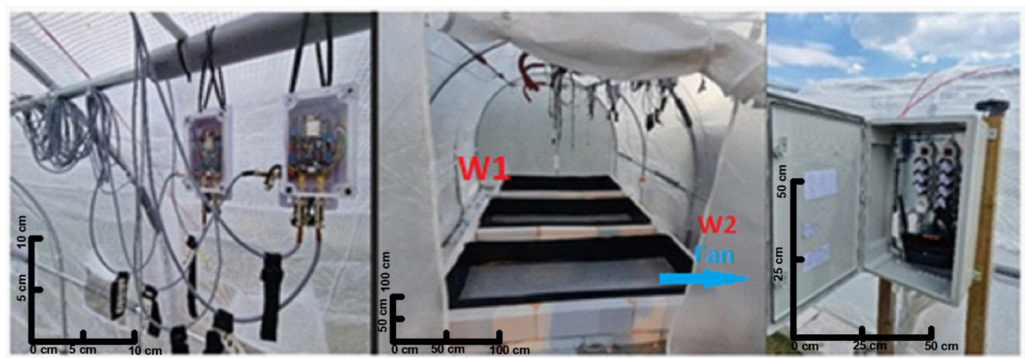


Figure 1. Measuring automation set for a solar drying tunnel.

The tunnel was equipped with a proprietary system for measuring and controlling solar drying parameters (Figure 1). An individual sensor suite was provided for each station, measuring air humidity (10–100%, $\pm 3\%$ RH), pressure (300–1110 hPa ± 1 hPa), temperature (-40 – 85 , ± 1 °C), insolation (0 – $1280 \pm 10 \text{ W/m}^2$), moisture and mixture temperature. (0 – $100\% \pm <2\%$; -10 – 85 , ± 0.5 °C). In addition, a separate suite was installed in the power supply unit to monitor external atmospheric conditions. Data was recorded continuously in the cloud. To ensure the highest possible temperature and air circulation inside the tunnel, two (opposite) windows out of 6 were left open, marked as W1 and W2 (Figure 1). Additionally, an electric fan was installed in window W2, which pushed air out of the tunnel, aiding the internal air circulation.

Three different variants of dewatered excess sewage sludge were prepared for testing with the addition of pine bark, wood chips, and walnut shells (Table 1). The sewage sludge was obtained from a local sewage treatment plant in the Poznań metropolitan area (Bytkowo WWTP).

Table 1. Characterisation of lignocellulosic materials and sewage sludge.

Name	Nitrogen Content, [% DM]	Carbon Content, [% DM]	Moisture, [%]	Bulk Density, [kg/dm ³]	Dry Organic Matter Content, [% DM Org]
Beech-alder wood chips	0.73	48.19	8.47	0.25	73.74
Pine bark (sorted)	1.13	50.06	52.05	0.15	65.01
Walnut shells	0.83	49.89	13.11	0.20	72.44
Sewage sludge	6.57	37.08	86.47	1.2	59.25

In the initial series of tests, three different additions of lignocellulosic materials were used: beech and alder wood chips, pine bark, and walnut shells, in a 50/50% volume ratio to the sludge. These tests allowed the type and amount of additive to be selected for the next series. The sludge and additive mixture had an initial moisture content of about 75%; drying continued until the water content was $\leq 20\%$. The drying time depended on the prevailing atmospheric conditions (insolation, temperatures, and humidity). The sewage sludge and walnut shell mixtures were mixed 5 times a week by manually turning the material from the bottom to the top. Table 1 includes a brief description of the materials used.

Various plant raw materials used for drying sludge did not give satisfactory results. The reason is their anatomical structure and the resulting high susceptibility to degradation processes. Beech or alder wood is characterized by large vessels and the ability to absorb significant amounts of water, but the conditions of drying the sediments also favour their degradation, and the reuse of these raw materials in the form of chips would require

additional energy-intensive drying processes, assessment of the degree of changes occurring and troublesome cleaning of the sediments. There is no need to perform these activities when using walnut shells. Their anatomical structure and chemical composition are significantly different and do not allow the absorption of significant amounts of water. However, the compact structure of the outer layer of shells causes easy separation of the dried sediment. Therefore, walnut shells were used in basic research.

In the basic series, the walnut shell additive added to the sludge was as follows (Table 2): 25%/75% (P1) and 40%/60% (P2) (by volume). One sludge drying station (P3) did not include additives and was left for use as a comparison.

Table 2. Research implementation schedule.

Number Series	Period Start	Period Endings	Type of Mixture
Preliminary research	7 September 2022	26 November 2022	W1—Pine bark 50%/Sewage sludge 50% W2—Beech-alder chips 50%/Sewage sludge 50% W3—Walnut shells 50%/Sewage sludge 50%
Basic series	26 January 2023	30 May 2023	P1—Walnut shells 25%/Sewage sludge 75% P2—Walnut shells 40%/Sewage sludge 60% P3—Sewage sludge 100%

2.1. Physical and Chemical Analyses

2.1.1. Moisture Content and Organic Dry Matter Content of Biomixtures 3—Drying Curve

The tests were based on direct measurements by direct weighing and were carried out at each experiment stage using a dryer (drying temperature: 105 °C), muffle furnace (combustion temperature: 550 °C), and analytical balance with an accuracy of 0.0001 g. The analyses were performed in accordance with the standard procedure.

2.1.2. Analysis of the Breaking Strength of Walnut Shells

The strength of walnut shells was determined using selected, cleaned shells from dried mixtures. As part of the test, the shells were compressed using a hydraulic press, and compression force was measured using a strain gauge. The test ended when the walnut shell broke. Each time, the shells were positioned convex side up. Twenty shells each from the W3, P1, and P2 mixtures and 20 “raw” shells not involved in the experiment were subjected to the strength test.

2.1.3. Walnut Shell Chemical Composition

Analysis of the walnut shells’ main and secondary constituents was carried out according to the relevant standards, i.e., cellulose was determined according to Seifert (1960) [47]; holocellulose according to Tappi—T9 wd-75 [48]; lignin according to Tappi—T-222 om-06 [49]; ethanol-soluble substances using the Soxhlet apparatus—Tappi T204 cm-07 [50]; ash according to DIN 51731 [51]; pentosans according to TAPPI—T 223 cm-01 [52].

2.1.4. Exhaust Gas and Element Analyses

Table 3 summarizes the parameters and measurement methodology.

The measurement was carried out using an A 550 L Thermodrucker TD 100 (Bad Wünnenberg, Germany) exhaust gas analyser equipped with the following measurement cells: CO, CO₂, NO_x, and SO₂. The measurement sensor was placed in the flue gas chimney of the experimental boiler. Measurements were performed in a single cycle with 3 repetitions. The measurement uncertainty range was calculated.

Table 3. Summary of parameters under study with the unit of measurement and test methodology.

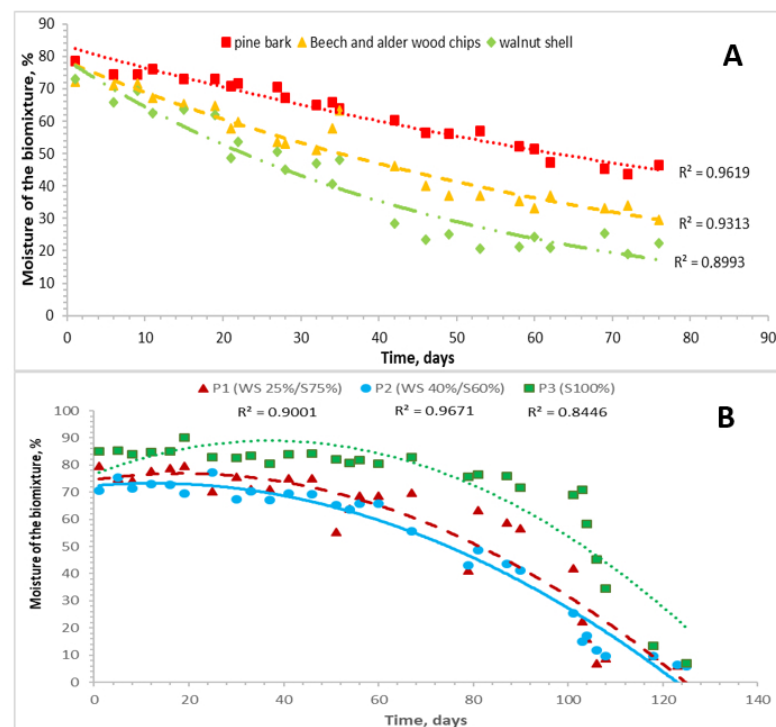
Parameter	Unit of Measurement	Survey Methodology
Total chlorine content	% s.m.	PN-EN ISO 16994:2016 [53]
Total moisture content	%	PN-EN ISO 18134-1 [54]
Total sulphur content	% d.m.	PN-EN ISO 21663:2021-06 [55]
Total hydrogen content	% d.m.	PN-EN ISO 21663:2021-06 [55]
Total carbon content	% d.m.	PN-EN ISO 21663:2021-06 [55]
Ash	% d.m.	PN-EN ISO 21656:2021-08 method A [56]
Heat of combustion (dry)	kJ/kg	PN-EN ISO 21654:2021-12 [57]
Calorific value (from dry calculations)	kJ/kg	PN-EN ISO 21654:2021-12 [57]
Kjeldahl nitrogen	% d.m.	PN-EN ISO 21663:2021-06 [55]
As, Cd, Cr, Cu, Ni, Pb, Zn	mg/kg d.m.	PN-EN ISO 11885:2009 [58]

2.1.5. Statistical Analysis

Statistical tests were used to assess the differences between the obtained series of results. Data distribution normality was checked using the Shapiro–Wilk test. In the case of a normal distribution, the Tukey parametric test was used, while in the case of a non-normal distribution, the Kruskal–Wallis non-parametric test was used. A significance level of $\alpha = 0.05$ was assumed.

3. Results

In a preliminary series of tests, it was found that in the time it took for the mixture of sludge and nut walnut shells to reach a moisture content of 20%, the mixture with woodchips reached 30% moisture content, and that with bark reached 45% (Figure 2A). Due to the mixture structure and drying time in the initial test series, walnut shells were chosen as an additive in the basic series.

**Figure 2.** Drying curves for the preliminary series of tests (A), drying curves for the basic test series (B).

During the test series, it was vital to maintain regular material mixing at the test stations, continuously record the technological parameters for the individual test stations, and regularly analyse the changes in the tested samples for each series in laboratory conditions.

3.1. Technological Parameters of Sewage Sludge Drying

Figure 3A shows the change in the temperature of the biomixture relative to air temperature and insolation in the basic series.

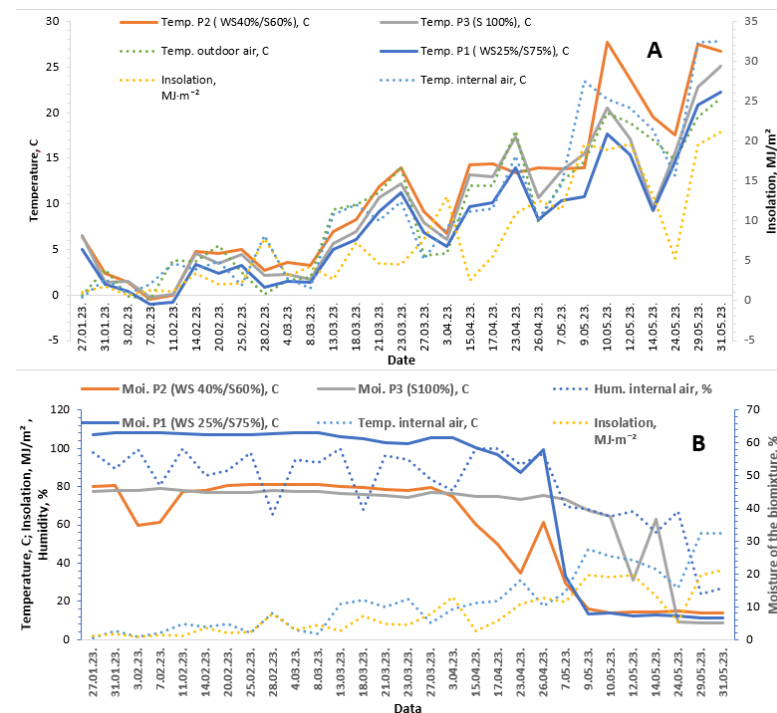


Figure 3. Graph showing temperature changes with respect to external factors in the basic series of tests (A), and graph showing humidity changes with respect to external factors during the basic series of tests (B).

The basic test series in winter and spring was characterised by uniform changes which occurred in the technological parameters of the mixture, depending on the duration of the tests, indicating an improvement in the recorded parameters along with changes in weather conditions, which significantly differed from those in the final phase of the experiment. The solar drying process at outdoor temperatures below or close to 0 °C was less effective than in temperatures above 0 °C. The analysis of the impact resulting from the amount of sludge bioadditive shows an improvement in the ability to maintain higher temperatures when more nut shells are used (40%—P2 mix). Figure 3B shows the change in the biomixture moisture content relative to external parameters.

Data on air humidity in the greenhouse tunnel, as recorded during the winter and spring research series, shows a tendency to maintain high air humidity inside. The air temperature inside the structure increased in line with the rising insolation, which improved during the winter and spring research series as the experiment progressed, mainly due to the sun exposure time, which provided more heat each month and positively influenced the biomixture solar drying process. The humidity continued to decrease along with the increase in insolation and the duration of the experiment. Sensors placed in the mixtures indicated that the moisture content of the sludge with added 40% nut shells (P2) decreased the fastest, having the highest moisture content, close to 70%, at the start of the drying process; the sludge doped with 25% nut shells (P1) started the drying process with a moisture content of 79%. The sludge with 40% nut shells (P2) showed the best properties and started to respond most quickly to the increase in temperature. The sludge containing 25% shells (P1) needed more time to reach parameters similar to the P2 sample. Analysis of the graph in Figure 3B indicates that the additives have a positive effect on the solar drying process, and the use of 25 and 40% additives reduces the time required to reach 20% moisture content by 14 days compared to the sludge without the bioadditive (P3).

Used to compare the differences in moisture content of the individual mixtures and the sludge without admixtures over time due to the non-normality of the data distribution, the Kruskal–Wallis statistical test indicated that it was impossible to reject the hypothesis that no differences existed between the controlled mixtures only for the compared mixtures with different walnut shell contents (P1:P2). This was because the probability p was greater than the significance level $\alpha = 0.05$. The results of the K-W test for the pairs of raw sludge-mixture with shells (P1:P3; P2:P3) enabled the rejection of the null hypothesis because the probability p was less than the significance level $\alpha = 0.05$. Hence, the conclusion is that there are significant differences between the drying parameters for the tested mixtures and the sludge without admixtures, as confirmed by the drying curves.

3.1.1. Mechanical Crushing Strength of Walnut Shells

The shells selected for hydraulic press testing were placed sequentially in the press. The direction of the crushing force in the tests was vertical; the shells were placed with the convex side facing the hydraulic press piston. The destructive force was 118.2 N for “raw” walnut shells, W3—112.28, P1—110.16 N, P2—123.61 N N for the mixture. There were slight differences between the values obtained, confirmed by the Kruskal–Wallis statistical test.

The small changes in shell strength after use in the biomixture suggest that the shells, once separated from the dried sludge, can be reused without concern for their mechanical destruction. This option will reduce the cost of drying sludge mixtures using walnut shells.

3.1.2. Walnut Shell Chemical Composition

Analysing the results of the chemical composition determinations of walnut shells (Table 4), it is noticeable that the raw material began to deteriorate despite the relatively short duration of the experiment. Following their use in the sludge dewatering process, the walnut shells’ basic chemical constituent content changed in small but noticeable amounts. The raw shells contained 30.06% cellulose. The same amount of cellulose in the nut shells (30.36%) was found by Domingos et al. (2022) [59]. Adding shells at a 40% ratio relative to the sludge resulted in a 2.3% loss of cellulose (0.7 percentage points). The total polysaccharide content of nut shells was 46–65% and was lower than that of wood biomass [46,60–62]. The raw husks contained 65.29% polysaccharides (holocellulose), and this amount did not change much during the experiment (Table 4).

Table 4. Chemical composition of walnut shells, main and secondary ingredients, % dry mass.

Trial Name	Raw WS 100%	P1 (WS 25%)	P2 (WS 40%)	W3 (WS 50%)
Cellulose [%]	30.06	30.01	29.37	29.6
Holocellulose [%]	65.29	65.25	64.93	65.95
Hemicellulose [%]	35.23	35.25	35.56	36.35
Lignina [%]	38.63	40.56	41.68	39.01
Substances diss. in EtOH [%]	1.7	1.15	1.14	1.28
Ash [%]	0.81	2.48	2.7	2.24
Pentosans [%]	29.02	28.22	28.01	27.57
L/H [%]	0.44	0.84	0.92	0.91
L/C [%]	0.39	1.27	1.59	1.26
L/HC [%]	0.56	1.62	2.44	1.61

The processes occurring during the drying of the sludge increased the amount of hemicelluloses to 36.35% compared to the starting material (35.23%). Hard nut shells are characterised by a high amount of lignin, containing more lignin than cellulose [59,61–63]. The shells tested contained 38.63% lignin (Table 4). During the sediment drying process, there was an increase in lignin content (from 1% in the case of the 50% shell addition to 7.8% in the case of the 40% shell addition), which may indicate changes in the degradation of the polysaccharide structure.

The amount of ethanol-extractable compounds ranged widely from 2.71% [59] to 4.6% [62]. The amount of ethanol-soluble substances changed significantly during the experiment. It decreased from 1.70% to 1.14% (Table 4), which also indicates the onset of changes in the main compound structure. Further, the change in the amount of pentosans—short-chain compounds—reaching as much as 5% confirms the beginning of these changes.

Significant changes can be seen when analysing the amount of ash in the shells. The raw nut shells contained a small amount of ash, i.e., 0.81%. Similar amounts of ash in walnut shells were found by Albatrni [46] and Queirós [61], i.e., 0.7%. Domingos [59] also reported the amount of ash in the shell at 1.3%. Pirayesh et al. (2012) [63] found 3.6% ash. The higher amount of ash may result from the growth conditions of the tree. The analysis of the ash content results showed that the tested nut shells (Table 4) contained between 2.24% and 2.70% ash after the experiment. There was a significant increase in the amount of these compounds.

To analyse the changes in the nut shells' structures during the experiment, infrared tests were performed using wavelengths ranging from 400 to 4000 cm^{-1} . As the spectra were similar, the parameters characterising the structure were determined from the absorbance values, and the following relationships were calculated: L/H—1510/1375 (lignin to hemicelluloses ratio); L/C—1510/1158 (lignin to cellulose ratio) and L/HC—1510/895 (lignin to C + H carbohydrates ratio). An already-published methodology was used to calculate the lignin-to-carbohydrate ratio [64,65]. The calculation was based on ratios of the heights of peaks specific for lignin 1510 cm^{-1} and carbohydrate groups 1374, 1158, and 897 cm^{-1} . The results are presented in Table 3.

By analysing the changes in absorbance recorded on the IR (Figure 4) spectra in the different wavebands, an increase in all ratios can be observed: L/H, L/C, and L/HC as compared to these relationships for the raw shells (Table 4). The greatest changes were observed in the shells added to the sludge at a ratio of 40%. These results are compatible with the chemical composition results and the changes that occurred in the shell structure after the experiment. They confirm the degradation of carbohydrate compounds in the shells that occurs during the drying of the sludge.

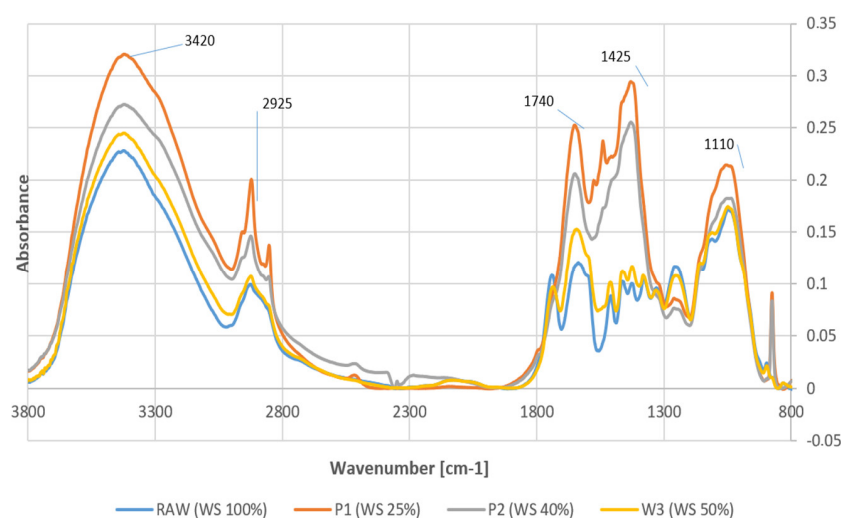


Figure 4. IR spectra of walnut shell mixtures.

Analyses of the so-called “wet” tests using chemical reagents showed no significant differences in raw nut shells and those after the sediment drying process. Instrumental IR analysis is a fast and accurate analysis indicating changes in structure, i.e., changes in the functional groups and bonds. In this case, it confirms minor changes in the shells after they had been used in the study. The authors did not consider it necessary to use other techniques for research because the changes were barely noticeable, which allowed the shells to be reused for drying sediments.

Based on the analyses, it can be concluded that the sludge causes changes in the walnut shell structure during drying. Despite its short duration, the experiment caused noticeable changes in the content of the main shell components. However, the thesis that the shells would be significantly degraded did not hold. The shells retained their structure, which enabled their reuse.

Walnut shells are waste from fruit production. Therefore, the results presented in Table are compared to the ISO 17225-7 [66] standard. The mixture marked as W3 meets the standards for chlorine, calorific value, mercury, cadmium, and lead.

Sewage sludge is a major source of elements and heavy metals, so the values in sample P3 are much higher than the walnut shell mixture. The addition of walnut shells increased the total carbon content, the heat of combustion, and calorific value in the analysed sample labelled W3 compared to “pure” P3 sewage sludge. The ash content, thanks to the addition of walnut shells, has decreased. These results are due to lignocellulosic compounds, which are the main components of the shells (Table 5).

Table 5. Physicochemical tests of mixtures.

Trial Name		W3 (WS 50%)	P3 (S100%)
Total moisture content	%	18.2	10.1
Total chlorine content		0.097	0.16
Total sulphur content		0.49	0.71
Total hydrogen content	% s.m.	5.34	5.03
Total carbon content		42.7	35.7
Ash		24.7	36.8
Kjeldahl nitrogen		2.7	4.5
Heat of combustion	kJ/kg	15,600	14,300
Calorific value		14,500	13,200
Mercury		0.1	0.1
As		5	5
Cd		0.23	0.61
Cr	mg/kg s.m.	7.2	19
Cu		120	400
Ni		19	28
Pb		6.7	8.8
Zn		200	630

Figure 5 presents the values of oxides of carbon, nitrogen, and sulphur gases. In accordance with the current EU directives on emission standards for biomass combustion, only the values of nitrogen oxides were exceeded. These values are caused by the addition of sewage sludge in the mixture.

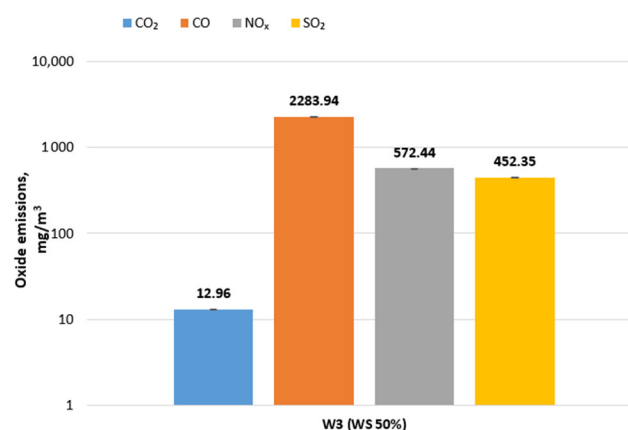


Figure 5. Values of gas oxides in the flue gas.

4. Discussion

Studies of the effect of walnut shells on solar drying parameters have shown an increase in the efficiency of the solar drying of sewage sludge, even with a 25% walnut shell addition to the sludge. The drying curves show an improvement in the ability to reduce sludge moisture with increasing amounts of additive during drying; however, the changes in moisture content of mixtures with different additive-to-sludge ratios showed no significant difference.

Analysis of the graphs showing the course of sludge solar drying revealed that the drying rate of the mixtures increased as the weather conditions improved. The quality of the mixtures differed significantly from the sewage sludge in terms of both structure and water content.

Considering the results of studies of facilities in Poland [67], one can conclude that sewage sludge drying is possible from spring to autumn due to the country's temperate climate. Between late autumn and spring, it is only possible to store and maintain the quality of dried sludge; however, a vital operational issue in this case is ventilating the drying tunnel [32,68]. Studies have shown that the walnut shell additive has reduced the drying period by approximately 30 days (in spring and winter conditions), enabling a faster commencement of raw sludge drying as early as the onset of spring. Additionally, this enables an increased sludge drying efficiency in a greenhouse under the same climate and facility conditions.

Studies of walnut shell chemical composition have shown that walnut shells contain approximately twice as many components responsible for strength as wood [60].

Studies of the crushing mechanical strength of walnut shells have shown slight differences in the mechanical strength of shells after mixture drying relative to "raw" shells. There was no change in the shells' shape or any significant change in their strength after drying, which was confirmed by a statistical test. The sewage sludge would separate from the shells by itself, forming small clumps. After separating the sewage sludge, e.g., using a drum sieve, the shells are suitable for further reuse.

The mixture made of natural material is fully biodegradable and is suitable as a fertiliser to improve soil structure as it contains approx. 80–90% DM (including approx. 40% carbon, 3% nitrogen, and other elements phosphorus and potassium.) and as an alternative fuel with parameters (calorific value and calorific value) depending on the amount of lignocellulosic additive. The values of mixtures are approximately 15% lower than wood biomass. The possibilities of using dried sewage sludge and mixtures are described in the work by Makowska [69]. The research results are consistent with the previously conducted experiments on this topic.

The possibilities of using dried sewage sludge and mixtures are described in the work by Makowska et al. 2020 [69]. The research results are consistent with previously conducted experiments on this topic. Walnut shells have a low ash content, and their calorific value is even higher than that of wood [70]. The addition of walnut shells increased the total carbon content, the heat of combustion, and the calorific value in the analysed mixture W3 compared to "pure" sewage sludge. Walnut shells are an undeveloped waste in Poland. They are used to a small extent as an abrasive in metalworking or as fuel. When used as a sewage sludge additive, walnut shells greatly improve the desired parameters of the sludge and can be reused repeatedly as a solar drying biocomponent.

5. Conclusions

Research has shown that using suitable additives to sewage sludge can affect the technological parameters during sludge solar drying. Such additives improve the structure of the mixture, reduce the process of putrefaction, and accelerate the process of sludge gelification. Desirable material characteristics include lightness, hardness, and low absorbability. Walnut shells offer all these qualities while also making the mixture highly porous. The study results show a positive effect on sludge quality and mixture water loss with as little as 25% walnut shell additive, which may translate into an increase in drying

capacity over the year. Despite the unfavourable environment that is hydrated sludge, the brief experiment time resulted only in noticeable changes in the content of the main shell components. However, the shells retained their structure and strength, which enabled their reuse in the solar drying process.

The authors of the article plan further research using walnut shells as a natural absorbent to remove heavy metals from sewage sludge during solar drying.

6. Patents

The results of the published research were included in patent application no. P.445919: “Technology for using natural materials for solar drying of sewage sludge and production of sewage sludge-based briquettes”.

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References

1. Cieřlik, B.M.; Namieřnik, J.; Konieczka, P. Review of sewage sludge management: Standards, regulations and analytical methods. *J. Clean. Prod.* **2015**, *90*, 1–15. [\[CrossRef\]](#)
2. Werle, S. Sewage Sludge-To-Energy Management in Eastern Europe: A Polish Perspective. *Ecol. Chem. Eng.* **2015**, *223*, 459–469. [\[CrossRef\]](#)
3. Przydatek, G.; Wota, A.K. Analysis of the comprehensive management of sewage sludge in Poland. *J. Mater. Cycles Waste Manag.* **2020**, *22*, 80–88. [\[CrossRef\]](#)
4. Council Directive of 21 May 1991 Concerning Urban Waste Water Treatment (91/271/EEC) the Council of the European Communities. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:31991L0271> (accessed on 8 August 2024).
5. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources. Available online: <https://eur-lex.europa.eu/eli/dir/2009/28/oj> (accessed on 8 August 2024).
6. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste. Available online: <https://eur-lex.europa.eu/eli/dir/2018/851/oj> (accessed on 8 August 2024).
7. Proposal for a Directive of the European Parliament and of the Council Concerning Urban Wastewater Treatment. 26 October 2022. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0541> (accessed on 8 August 2024).
8. Bałazińska, M.; Markowska, M.; Blaut, A.; Głodniok, M. Life Cycle Assessment of Eco-Innovative Organo-Mineral Granulated Fertilizer’s Production Technology. *Rocz. Ochr. Śr.* **2020**, *22*, 561–588.
9. Hurynovich, A.; Kwietniewski, M.; Romanovski, V. Evaluation of the possibility of utilization of sewage sludge from a wastewater treatment plant-case study. *Desalin. Water Treat.* **2021**, *227*, 16–25. [\[CrossRef\]](#)
10. Piechota, G.; Igliński, B. Biomethane in Poland—Current Status, Potential, Perspective and Development. *Energies* **2021**, *14*, 1517. [\[CrossRef\]](#)
11. Posligua, P.; Peñaherrera, M.; Villegas, E.; Banchón, C. Gravimetric Evolution During Sewage Sludge Biostabilization. *J. Ecol. Eng.* **2018**, *195*, 76–85. [\[CrossRef\]](#)
12. Możdźer, E. Effect of Fertilization with Sludge-Ash Granulates on the Activity of Selected Soil Enzymes. *J. Ecol. Eng.* **2022**, *234*, 137–144. [\[CrossRef\]](#)
13. Hajji, S.; Ben-Haddad, M.; Rida Abelouah, M.; De-la-Torre, G.E.; Ait Alla, A. Sludge drying and dewatering processes influence the abundance and characteristics of microplastics in wastewater treatment plants. *Chemosphere* **2023**, *339*, 139743. [\[CrossRef\]](#)

14. Kosiński, P.; Kask, B.; Franus, M.; Piłat-Rożek, M.; Szulżyk-Cieplak, J.; Łagód, G. The Possibility of Using Sewage Sludge Pellets as Thermal Insulation. *Adv. Sci. Technol. Res. J.* **2023**, *172*, 161–172. [\[CrossRef\]](#)
15. Mehrdadi, N.; Joshi, S.G.; Nasrabadi, T.; Hoveidi, H. Application of solar energy for drying of sludge from pharmaceutical industrial waste water and probable reuse. *Int. J. Environ. Res.* **2007**, *1*, 42–48.
16. Khan, R.; Shukla, S.; Kumar, M.; Zuorro, A.; Pandey, A. Sewage sludge derived biochar and its potential for sustainable environment in circular economy: Advantages and challenges. *J. Chem. Eng.* **2023**, *471*, 144495. [\[CrossRef\]](#)
17. Zhen, G.; Lu, X.; Kato, H.; Zhao, Y.; Li, Y.Y. Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: Current advances, full-scale application and future perspectives. *Renew. Sust. Energy Rev.* **2017**, *69*, 559–577. [\[CrossRef\]](#)
18. Cesaro, A.; Pirozzi, F.; Zafirakou, A.; Alexandraki, A. Microplastics in sewage sludge destined to anaerobic digestion: The potential role of thermal pretreatment. *Chemosphere* **2022**, *309*, 136669. [\[CrossRef\]](#)
19. Yusuf, H.H.; Roddick, F.; Jegatheesan, V.; Gao, L.; Pramanik, B.K. Tackling fat, oil, and grease FOG build-up in sewers: Insights into deposit formation and sustainable in-sewer management techniques. *Sci. Total Environ.* **2023**, *904*, 166761. [\[CrossRef\]](#)
20. Jat Baloch, M.Y.; Zhang, W.; Sultana, T.; Akram, M.; Shoumik, B.A.; Al Khan, M.Z.; Farooq, M.A. Utilization of sewage sludge to manage saline-alkali soil and increase crop production: Is it safe or not? *Environ. Technol. Innov.* **2023**, *32*, 103266. [\[CrossRef\]](#)
21. Syed-Hassan, S.S.A.; Wang, Y.; Hu, S.; Su, S.; Xiang, J. Thermochemical processing of sewage sludge to energy and fuel: Fundamentals, challenges and considerations. *Renew. Sustain. Energy Rev.* **2017**, *80*, 888–913. [\[CrossRef\]](#)
22. An-nori, A.; El Fels, L.; Ezzariai, A.; El Gharous, M.; El Mejahed, K.; Hafidi, M. Effects of solar drying on heavy metals availability and phytotoxicity in municipal sewage sludge under semi-arid climate. *Environ. Technol. Innov.* **2020**, *19*, 101039. [\[CrossRef\]](#)
23. Fan, Z.; Zhou, X.; Peng, Z.; Wan, S.; Gao, Z.F.; Deng, S.; Tong, L.; Han, W.; Chen, X. Co-pyrolysis technology for enhancing the functionality of sewage sludge biochar and immobilizing heavy metals. *Chemosphere* **2023**, *317*, 137929. [\[CrossRef\]](#)
24. Krawczyk, P. Numerical Modeling of Simultaneous Heat and Moisture Transfer During Sewage Sludge Drying in Solar Dryer. *Procedia Eng.* **2016**, *157*, 230–237. [\[CrossRef\]](#)
25. Kosińska, N.; Krzyżyńska, R.; Ghazal, H.; Jouhara, H. Hydrothermal carbonisation of sewage sludge and resulting biofuels as a sustainable energy source. *Energy* **2023**, *275*, 127337. [\[CrossRef\]](#)
26. Kowalczyk-Juśko, A.; Mazur, K.; Maciag, M.; Pochwatka, P.; Listosz, A.; Mazur, A. Estimation of Potential of Agriculture Biogas Production in Biała Podlaska County Poland. *J. Ecol. Eng.* **2020**, *218*, 156–162. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Piboonudomkarn, S.; Khemthong, P.; Youngjan, S.; Wantala, K.; Tanboonchuy, V.; Lubphoo, Y.; Khunphonoi, R. Co-hydrothermally carbonized sewage sludge and lignocellulosic biomass: An efficiently renewable solid fuel. *Arab. J. Chem.* **2023**, *1612*, 105315. [\[CrossRef\]](#)
28. Wzorek, M. Solar drying of granulated waste blends for dry biofuel production. *Environ. Sci. Pollut. Res.* **2021**, *2826*, 34290–34299. [\[CrossRef\]](#)
29. Smol, M. Inventory of Wastes Generated in Polish Sewage Sludge Incineration Plants and Their Possible Circular Management Directions. *Resources* **2020**, *9*, 91. [\[CrossRef\]](#)
30. Boguniewicz-Zablocka, J.; Klosok-Bazan, I.; Capodaglio, A.G. Sustainable management of biological solids in small treatment plants: Overview of strategies and reuse options for a solar drying facility in Poland. *Environ. Sci. Pollut. Res. Int.* **2021**, *2819*, 24680. [\[CrossRef\]](#)
31. Tańczuk, M.; Kostowski, W.; Karaś, M. Applying waste heat recovery system in a sewage sludge dryer—A technical and economic optimization. *Energy Convers. Manag.* **2016**, *125*, 121–132. [\[CrossRef\]](#)
32. Krawczyk, P. Control strategy for ventilation system of sewage sludge solar dryer. *J. Power Technol.* **2016**, *96*, 145–148.
33. Czekala, W.; Dach, J.; Janczak, D.; Smurzyńska, A.; Kwiatkowska, A.; Kozłowski, K. Influence of maize straw content with sewage sludge on composting process. *J. Water Land. Dev.* **2016**, *301*, 43–49. [\[CrossRef\]](#)
34. Czekala, W.; Nowak, M.; Piechota, G. Sustainable management and recycling of anaerobic digestate solid fraction by composting: A review. *Bioresour. Technol.* **2023**, *375*, 128813. [\[CrossRef\]](#)
35. Matias Gonçalves, L.; Mendoza-Martinez, C.; Alves Rocha, E.P.; Coutinho de Paula, E.; Cardoso, M. Solar Drying of Sludge from a Steel-Wire-Drawing Industry. *Energies* **2023**, *16*, 6314. [\[CrossRef\]](#)
36. Calín-Sánchez, Á.; Lipan, L.; Cano-Lamadrid, M.; Kharaghani, A.; Masztalerz, K.; Carbonell-Barrachina, Á.A.; Figiel, A. Comparison of Traditional and Novel Drying Techniques and Its Effect on Quality of Fruits. *Veg. Aromat. Herbs Foods Basel.* **2020**, *9*, 1261. [\[CrossRef\]](#)
37. Mayanja, I.K.; Coates, M.C.; Niederholzer, F.; Donis-González, I.R. Drying of freshly harvested almonds using a stockpile heated and ambient air dryer SHAD with an air distributor-part 2. *Biosyst. Eng.* **2023**, *235*, 189–201. [\[CrossRef\]](#)
38. Mhd Safri, N.A.; Zainuddin, Z.; Mohd Azmi, M.S.; Zulkifli, I.; Fudholi, A.; Ruslan, M.H.; Sopian, K. Current status of solar-assisted greenhouse drying systems for drying industry food materials and agricultural crops. *Trends Food Sci. Technol.* **2021**, *114*, 633–657. [\[CrossRef\]](#)
39. Saini, R.K.; Saini, D.K.; Gupta, R.; Verma, P.; Thakur, R.; Kumar, S.; Wassouf, A. Technological development in solar dryers from 2016 to 2021—A review. *Renew. Sust. Energy Rev.* **2023**, *188*, 113855. [\[CrossRef\]](#)
40. Lewandowski, W.M. *Pro-Ecological Renewable Energy Sources*; WNT: Warszawa, Poland, 2012.
41. Afshari, F.; Khanlari, A.; Tuncer, A.D.; Sözen, A.; Şahinkesen, I.; Di Nicola, G. Dehumidification of sewage sludge using quonset solar tunnel dryer: An experimental and numerical approach. *Renew. Energy* **2021**, *171*, 784–798. [\[CrossRef\]](#)

42. Getahun, E.; Delele, M.A.; Gabbiye, N.; Fanta, S.W.; Demissie, P.; Vanierschot, M. Importance of integrated CFD and product quality modeling of solar dryers for fruits and vegetables: A review. *Sol. Energy* **2021**, *220*, 466–468. [CrossRef]
43. Horn, S.; Barr, K.; McLellan, J.; Bux, M. Accelerated Air Drying of Sewage Sludge Using a Climate Controlled Solar Drying Hall. 2020. Available online: <https://www.thermo-system.com> (accessed on 8 August 2024).
44. Das, M.; Akpinar, E.K. Determination of thermal and drying performances of the solar air dryer with solar tracking system: Apple drying test. *Case Stud. Therm. Eng.* **2020**, *21*, 00731. [CrossRef]
45. Karaağaç, M.O.; Ergün, A.; Ağbulut, Ü.; Gürel, A.E.; Ceylan, İ. Experimental analysis of CPV/T solar dryer with nano-enhanced PCM and prediction of drying parameters using ANN and SVM algorithms. *Sol. Energy* **2021**, *218*, 57–67. [CrossRef]
46. Albatrni, H.; Qiblawey, H.; Al-Marri, M.J. Walnut shell based adsorbents: A review study on preparation, mechanism, and application. *J. Water Process Eng.* **2022**, *45*, 102527. [CrossRef]
47. Seifert, K. Zur frage der cellulose-schnellbestimmung nach der acetylaceton-methode. *Das Papier* **1960**, *14*, 104–106. (In German)
48. TAPPI T 9 wd-75; Holocellulose in Wood. Technical Association of the Pulp and Paper Industry (TAPPI): Atlanta, GA, USA, 2006.
49. TAPPI T-222 om-06; Standard Methods for Acid Insoluble Lignin in Wood and Pulp. Technical Association of Pulp and Paper Industry: Atlanta, GA, USA, 2006.
50. TAPPI T 204 cm-07; Solvent Extractives of Wood and Pulp. Technical Association of the Pulp and Paper Industry (TAPPI): Atlanta, GA, USA, 2007.
51. DIN 51731:1996; Testing of Solid Fuels—Compressed and Untreated Wood—Requirements and Testing. German Institute for Standardization: Berlin, Germany, 1996.
52. TAPPI-T 223 cm-01; Pentosans in Wood and Pulp. Technical Association of the Pulp and Paper Industry (TAPPI): Atlanta, GA, USA, 2001.
53. PN-EN ISO 16994:2016; Solid Biofuels—Determination of Total Content of Sulfur and Chlorine. Polish Committee for Standardization: Warsaw, Poland, 2016.
54. PN-EN ISO 18134-1; Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 1: Total Moisture—Reference Method. Polski Komitet Normalizacyjny: Warszawa, Poland, 2016.
55. PN-EN ISO 21663:2021-06; Solid Recovered Fuels—Determination of Total Content of Carbon, Hydrogen and Nitrogen. Polski Komitet Normalizacyjny: Warszawa, Poland, 2021.
56. PN-EN ISO 21656:2021; Solid Recovered Fuels—Determination of Ash Content. Polski Komitet Normalizacyjny: Warszawa, Poland, 2021.
57. PN-EN ISO 21654:2021-12; Solid Recovered Fuels—Determination of Calorific Value. Polski Komitet Normalizacyjny: Warszawa, Poland, 2021.
58. PN-EN ISO 11885:2009; Water Quality—Determination of Selected Elements by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Polski Komitet Normalizacyjny: Warszawa, Poland, 2009.
59. Domingos, I.; Ferreira, J.; Cruz-Lopes, L.P.; Esteves, B. Liquefaction and chemical composition of walnut shells. *Open Agric.* **2022**, *7*, 249–256. [CrossRef]
60. Prosiński, S. *Chemia Drewna*; PWRiL: Warszawa, Poland, 1984; ISBN 83-09-00674-8.
61. Queirós, C.S.G.P.; Cardoso, S.; Lourenço, A.; Ferreira, J.; Miranda, I.; Lourenço, M.J.V.; Pereira, H. Characterization of walnut, almond, and pine nut shells regarding chemical composition and extract composition. *Biomass Convers. Biorefin.* **2020**, *10*, 175–188. [CrossRef]
62. Queirós, C.S.G.P.; Cardoso, S.; Ferreira, J.; Miranda, I.; Lourenço, M.J.V.; Pereira, H. Characterization of Hakea sericea Fruits Regarding Chemical Composition and Extract Properties. *Waste Biomass Valorization* **2020**, *11*, 4859–4870. [CrossRef]
63. Pirayesh, H.; Khazaeian, A.; Tabarsa, T. The potential for using walnut *Juglans regia* L. shell as a raw material for wood-based particleboard manufacturing. *Compos. B Eng.* **2012**, *43*, 32763280. [CrossRef]
64. Pandey, K.K.; Pitman, A.J. FTIR studies of the changes in wood chemistry following decay by brown-rot and white-rot fungi. *Int. Biodeterior. Biodegrad.* **2003**, *52*, 151–160. [CrossRef]
65. El Hadidi, N.M.N. Decay of softwood in archaeological wooden artifacts. *Stud. Conserv.* **2017**, *62*, 83–95. [CrossRef]
66. PN-EN ISO 17225-7; Solid Biofuels—Fuel Specifications and Classes—Part 7: Graded Non-Woody Briquettes. Polski Komitet Normalizacyjny: Warszawa, Poland, 2021.
67. Trojanowska, K. Economics of sewage sludge drying plants—A review of the first decade of Polish experience. *Exploitation. Forum.* **2016**, *3*, 56–63.
68. Krawczyk, P. The relative change of drying rate as a function of the cumulative ventilation air drying potential in a thin-layer solar drying facility. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *556*, 012055. [CrossRef]
69. Makowska, M.; Kujawiak, S.; Pawlak, M.; Sowińska, A. Energy use of a biomixture based on sewage sludge. Assessment of sewage and sludge management. In *Poland. Report. PAN Monographs of the Environmental Engineering Committee*, 1st ed.; Bień, J., Gromiec, M., Pawłowski, L., Eds.; Committee of Environmental Engineering: Lublin, Poland, 2020; Issue 166.
70. Zajemska, M.; Musiał, D. Energy use of biomass from agricultural production in co-combustion process. *Probl. Agric. Eng.* **2013**, *4*, 107–118.

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