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Changes in the Characteristics of Pine Logging Residue during Storage in Forest Stands

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Abstract: A significant amount of logging residue is produced during roundwood harvesting. Logs are often left in forest sites due to, for example, ecological or logistical aspects. Taking into account the fact that the number of studies focused on changes in the properties of the residue is very low, it was decided to conduct research on the effect of a three-year storage period in forest stands on the chemical properties and energy potential of the wood. The research design allowed for the determination of changes during up to three years of storage. The performed analysis showed a highly negative impact on the characteristics of the material. These adverse effects were probably caused by the activity of microorganisms such as fungi and bacteria, as evidenced by the increased concentrations of ergosterol and low-molecular-weight organic acids. Moreover, it was found that wood stored for three years was characterized by a lower cellulose content; an increased percentage of lignin; a reduced content of sterols (desmosterol, stigmasterol, lanosterol and β-sitosterol) and phenolic acids; and reduced antioxidant activity, as determined with the $ABTS^+$ method. Storing logs also led to a reduction in the energy potential of the residues, as shown by a reduction in net and gross calorific value and an increased ash content.

Keywords: logging residues; biodeterioration; storage; chemical composition; calorific value

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1. Introduction

Logging residues are a product of the harvesting of round wood for various purposes. According to Shmulsky and Jones [1], the annual global consumption of roundwood reached 3.71 billion cubic meters, which means that these types of residue are produced in significant quantities. Obtained roundwood is further processed in many industrial fields: paper production, wood-based materials production, furniture production, firewood production and production of structural elements [2]. The form and amount of residue generated may depend on various factors, for example, the harvesting method, the level of mechanization, the dominant species, the age of the tree stand, and the thickness, height and quality of the tree [3,4]. Residues usually include fine wood materials (less than 7 cm in diameter) and thicker wood materials (with a diameter of more than 7 cm) [5]. Moreover, they often also include other types of forest biomass, e.g., leaves, needles, cones, bark and branches with a diameter ranging from 3 to 7 cm [6,7]. During roundwood harvesting, the short and long logs obtained for various processing purposes are transported to the roadside while the residues are usually left at the forest sites in designated small piles [8,9].

The yield of residues usually ranges from 30 to over 200 tons per hectare; the lowest values are, in most cases, recorded for Mediterranean and boreal forests and the highest for poplar and pine plantations [10–13]. In the case of Polish pine forests, which constitute over 60% of the total forest area, the log harvesting method used generates a much larger volume of residue than in the case of large-sized roundwood harvesting—78 t/ha and 32 t/ha, respectively [14]. In one study, when clear-cutting pine stands, the amount of logging residue was 44.7 t/ha [15], while another study performed by Beardsell [16] showed a yield of 75.4 t/ha. Interesting outcomes were also obtained for species other than pine. In one eucalyptus logging operation the mass of created residue was 106.5 t/ha and for Norwegian spruce the mass ranged from 19.4 to 49.9 t/ha [7,17]. Regardless of the amount and type of residue generated, according to Zyryanov et al. [18], one of the main directions in the development of a complex forest system is to find a potential use for all wood material, residues included; therefore, it is necessary to investigate the changes in the characteristics of these materials.

From a forest management perspective, the reasons for logging residue removal include the reduction in fire risk and the preparation of area for planting new trees [19]. On the other hand, as shown by Smolander et al. [20], the presence of logging residue improves the tree and stand features and the content of nutrients contained in the soil. These residues may also have other ecological benefits such as protection against soil erosion and improving water filtration. Research conducted in European countries has shown that too intensive biomass removal may have a negative impact on forest stands [21,22]. The environmental response to such activities depends, among others, on the characteristics of the area, and the composition and amount of recovered biomass [10]. Removal of residues should be especially avoided in the case of low-quality soils to help maintain the already low levels of nutrients [21,23]. It may even affect the growth of trees, especially when the various types of green biomass, such as leaves, are removed [24–26]. Nevertheless, the utilization of these residues may also contribute to increasing income from forest cultivation [10]. They can be used, for example, in the process of bioenergy production and the production of chips used in horticulture [27]. However, in some cases, difficult access to the harvesting site may be an obstacle to removing the remains. The recovery of post-logging biomass in forests is estimated to be over 52% [28]. In Finland, it is recommended to have at least 30% of wood residues left on site, while in France it is recommended to leave at least 10% of fine materials on non-sensitive soils and at least 30% on moderately sensitive soils [5,21]. Furthermore, in the case of the Pacific North West, the USDA (United States Department of Agriculture) guidelines says that at least 4–5% of residues should be left on the operation site [29]. Overall, a large amount of biomass remains in the forest environment but the amount of research focused on the changes in its properties is, to date, very low.

Wood logging residues left on operation sites continue to play an important role from ecological perspective because they become available to other living organisms, which slowly degrade them [30–32]. Considering the large biodiversity of forests, there is a very large number of organisms which can contribute to the wood decomposition [3,33]. Thus, the aim of presented research was to investigate the changes in the chemical composition and calorific value of pine logging residues stored in forest stands for up to 3 years.

2. Materials and Methods

2.1. Storage of Residues and Collecting the Samples

The research material was obtained while logging pine trees (*Pinus sylvestis* L.) in a forest site. To investigate the effect of biodeterioration of residues on the characteristics of wood, four different research areas located close to each other were selected. In the first area, wood material was freshly obtained in May 2023 and it was used as reference. In the second area, the residues were stored for one year from May 2022 to May 2023, in third area, the residues were stored for two years from May 2021 to May 2023 and in the fourth area, the residues were stored for three years from May 2020 to May 2023. An example of a

research area is shown in Figure 1, and the detailed location characteristics of individual areas are presented in Table 1 and Figure 2.



Figure 1. A typical research area.

Table 1. Description of research areas based on data collected from the Forest Data Bank [34].

Characteristics	Fresh Residues	Residues Stored for 1 Year	Residues Stored for 2 Years	Residues Stored for 3 Years
Coordinates	52°37′93″ N 15°72′24″ E	52°38′61″ N 15°73′33″ E	52°38′64″ N 15°73′65″ E	52°38′76″ N 15°73′16″ E
Forest address	10-29-1-04-433-g-00	10-29-1-04-378-b-00	10-29-1-04-377-a-00	10-29-1-04-378-a-00
Area (ha)	1.20	4.87	13.58	2.68
Forest district	Trzciel, PL	Trzciel, PL	Trzciel, PL	Trzciel, PL
Forest habitat	Fresh mixed forest	Fresh mixed forest	Fresh mixed forest	Fresh mixed forest
Dominant species	Scots pine	Scots pine	Scots pine	Scots pine
Age of dominant species	60	61	64	68

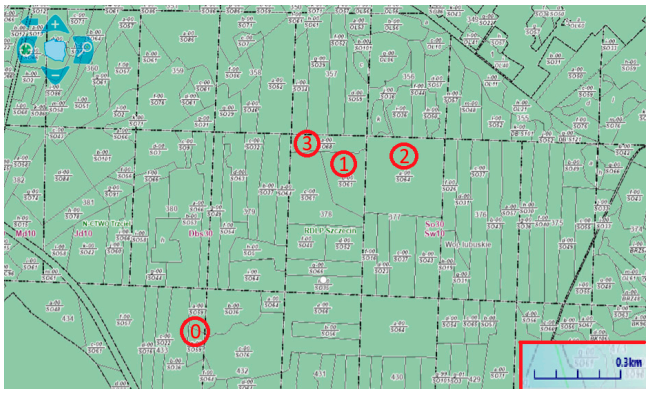


Figure 2. Location of the research areas based on the Forest Data Bank [34] (0—location for collecting reference residues, 1—location of storing the residues for 1 year, 2—location of storing the residues for 2 years and 3—location of storing the residues for 3 years).

Research material was collected only in the form of thick branches with a diameter of 7 cm. This represented the largest volume fraction and constituted approx. 30–40% of the residues, regardless of the type of forest site. Moreover, thick branches are considered the most attractive type of residue due to their much greater energy potential compared to, for example, small branches, bark, cones or leaves [10,35–38]. The samples also did not contain green forest biomass, such as cones, needles or leaves, because their presence could make it difficult to interpret the changes in chemical composition. Branches were cut to obtain sections of approx. 10 cm long. To obtain the most representative sample

possible, both branches lying in contact with the ground and those located slightly above the ground were selected. A knife mill was used to grind the obtained branches. These mills are often used for shredding plant material and are especially effective when cutting high-moisture biomass [39,40]. Then, collected sections were dried in a laboratory oven to a moisture content ranging from 10 to 12%. The obtained chips were further ground in a laboratory mill to obtain a dimensional fraction of 0.1–0.4 cm, which was intended for chemical analyzes in accordance with the TAPPI (Technical Association of the Pulp and Paper Industry) standard T 264 cm-07 [41]. A schematic presentation of the method used to prepare the wood material for analysis is shown in Figure 3.



Figure 3. Preparation of research material for analysis: (**a**) processing the branches into sections, (**b**) wood chips obtained after first grinding; (**c**) wood powder obtained after milling.

2.2. Determination of Cellulose and Lignin Content

Analysis of cellulose and lignin content was performed in triplicate. The Seifert method, with a mixture of acetylacetone, 1,4-dioxane and hydrochloric acid, was used to determine the cellulose content [42].

Content of acid-insoluble lignin was determined using 72% sulfuric acid according to the TAPPI T 222 om-06 standard [43].

2.3. Determination of Sterol Content

The sterol content in logging residues was determined in triplicate by microwave-assisted basic hydrolysis. Before the analysis, samples of ground wood powder were dissolved in 1 mL of methanol and filtered through a syringe filter with a pore diameter of 0.22 µm. The sterol content in each residue variant was analyzed with an Acquity H class UPLC system with a Waters Acquity PDA detector (Milford, MA, USA). Chromatographic separation was carried out using an Acquity UPLC BEH® C18 column (Waters, Dublin, Ireland) (100 mm × 2.1 mm, particle size of 1.7 µm). Elution was performed isocratically with the use of the following mobile phase: A—acetonitrile (10%), B—methanol (85%) and C—water (5%) and a flow of 0.5 mL/min. Determination of sterol concentration was conducted using the external standard at wavelengths of λ = 210 nm (desmosterol, lanosterol, stigmasterol and β-sitosterol) and λ = 282 nm (ergosterol). Individual compounds were identified by comparing the retention time of the examined peak with the standard by the addition of specific amounts of the standard to the sample and a repeat of the analysis. The limit of detection was 0.1 mg/kg [44,45].

2.4. Determination of Low Molecular Weight Organic Acid (LMOWA) Content

The LMOWA content was analyzed in triplicate using an Acquity H class UPLC system equipped with a Waters Acquity PDA detector (Milford, MA, USA). The chromatographic separation was performed on an Acquity UPLC BEH C18 column (150 mm × 2.1 mm, particle size of 1.7 µm), thermostated at 35 °C. The gradient elution was performed with water and acetonitrile (both containing 0.1% formic acid, pH = 2) at a flow rate of 0.4 mL/min. Compounds were identified by comparing the retention time of the analyzed peaks with the retention time of standards or by adding a specific amount of the standard to the analyzed

samples and repeating the analysis. Detection was carried out in a Waters Photodiode Array Detector at λ = 280 nm using an external standard. The quantification was performed by comparing the area of the peaks recorded at 280 nm and the calibration curve obtained from the commercial standards of each compound [46,47].

2.5. Determination of Total Phenolic Acid (TPA) Content

Total phenolic acid content was analyzed in triplicate using Acquity UPLC chromatography (Milford, MA, USA) with a Waters Acquity PDA detector on an Acquity UPLC BEH C18 column (100 mm × 2.1 mm, particle size of 1.7 µm) at a wavelength of λ = 320 nm relative to the blind test. The sample injection volume was 10 µL, and the flow rate was 0.4 mL/min. The isocratic elution was performed using a mobile phase, which was a mixture of A—formic acid solution in acetonitrile (0.1%) and B—aqueous formic acid solution (0.1%). The total phenolic acid content was expressed as mg gallic acid equivalent per gram (mg GAE/g) by comparison with the caffeic acid calibration curve. The range of the calibration curve was 10–1000 mg/L (r^2 = 0.9982) [46].

2.6. Antioxidant Activity ($ABTS^+$ Method)

For $ABTS^+$ generation from ABTS salt, 3 mM of $K_2S_2O_8$ was reacted with 8 mM ABTS salt in distilled, deionized water at room temperature, for 16 h, in the dark. Then, the $ABTS^+$ solution was diluted with a pH 7.4 phosphate buffer solution containing 150 mM NaCl (PBS) to obtain the initial absorbance of 1.5 at 730 nm. A fresh $ABTS^{\cdot+}$ solution was prepared for each analysis. Reaction kinetics were analyzed over a 2 h period with readings every 15 min. Reactions were complete in 30 min. Samples and 100 µm of standards were reacted with the $ABTS^{\cdot+}$ solution (2900 µm) for 30 min. Trolox was used as a standard. Results are expressed as average from three repetitions, in µmol of TROLOX per 100 g of dried sample [44,48].

2.7. Determination of Ash Content and Net and Gross Calorific Values

The gross and net calorific values of the samples were evaluated in three repetitions with the use of an IKA C200 calorimeter (IKA®-Werke GmbH & Co. KG, Staufen, Germany) according to STN ISO 1928 [49]. Moreover, one sample from each variant was used to determine the ash content according to EN ISO 18122 [50].

2.8. Statistical Analysis

The statistical analysis was conducted using STATISTICA 13.0 software. The significance of differences observed between the variants was assessed by one-way analysis of variance (ANOVA) followed by the Tukey HSD test at a significance level of $\alpha = 0.05$.

3. Results and Discussion

As shown in Figure 4, the logging residues experienced a significant change in chemical composition during storage. The results shown in Figure 4A indicate that as the storage time increased, the cellulose content gradually decreased. Compared to freshly obtained residues, the cellulose content was lower by 9, 11 and 17% after storing for 1 year, 2 years and 3 years, respectively. Considering that cellulose is the main structural polymer in plant cell walls, its content significantly affects, for example, the strength, stiffness and hydrophilicity of wood [51,52]. The reduction in cellulose content can be related to autooxidation and exposure to ultra-violet light especially in the presence of oxygen and high moisture [53,54]. In addition, biological factors such as fungi and bacteria can lead to aerobic and anaerobic degradation of polysaccharides [55]. On the other hand, as shown in Figure 4B, lignin content increased by up to 35% during the three-year storage period. The reason for this phenomenon was probably the decrease in cellulose content, which resulted in an increase in the percentage share of lignin [56].

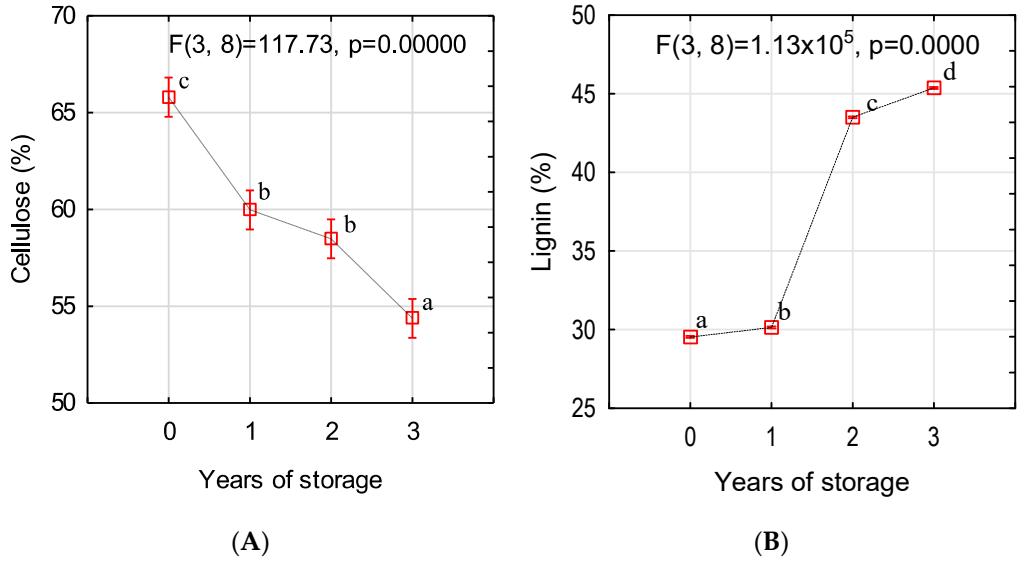


Figure 4. Changes in the chemical composition of residues: (**A**) cellulose content and (**B**) lignin content. (a–d letters indicate homogeneous groups).

Figure 5 presents the results of ergosterol (ERG) content investigations. Based on the outcomes, it was found that ERG content significantly increased during storage from a value below the detection limit to 405.97 mg/kg. This is consistent with the decreasing cellulose content, which indicated fungal activity because ERG is a fungal marker commonly used for determination of various materials' contamination with mycobiota [57,58]. ERG is a fungal membrane lipid present in both living and dead forms of fungi [59,60]. Previously conducted studies on the contamination of wood chips have shown that there is a high correlation between the concentration of ERG and the concentration of fungal spores [61]. Therefore, such a high concentration indicates the increasing deterioration of the logging residues by fungi, which could be expected considering the significant biodiversity of forest environments and, at least periodically, the high moisture content of wood.

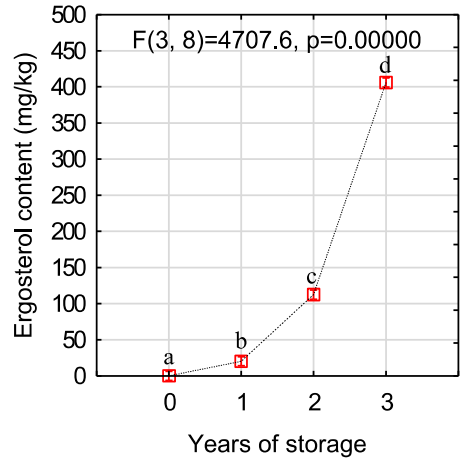


Figure 5. Changes in ergosterol content. (a–d letters indicate homogeneous groups).

The content of selected sterols such as desmosterol, lanosterol, stigmasterol and β-sitosterol, which were considered by Rogoziński et al. [62] to be the most important sterols in wood, was measured and the results are summarized in Figure 6. These sterols are natural organic compounds representing the isoprenoid class. They are integral components of the membrane lipid layer and are crucial for many processes occurring in plants, such as growth regulation and stress resistance [63]. As shown by the results, the content of all

analyzed sterols decreased significantly during storage. The content of desmosterol was reduced by up to 68%, lanosterol by up to 67%, stigmasterol by up to 66% and β-sitosterol by up to 53% as a result of the three-year storage period. These outcomes can be an indicator of significant fungal activity. Wood logging residues are dead tissue; therefore, sterols no longer play a role in the defense mechanisms [45]. On the contrary, fungi utilize these sterols when growing on the surface of wood [44]. According to Gutierrez et al. [64], sterols are considerably more susceptible to degradation by fungi compared to different lipid compounds such as triglycerides, hydrocarbons and steroid ketones. Therefore, the decreasing concentrations of the analyzed sterols may indicate the progressive decomposition of the pine logging residues by fungi during storage in forest stands.

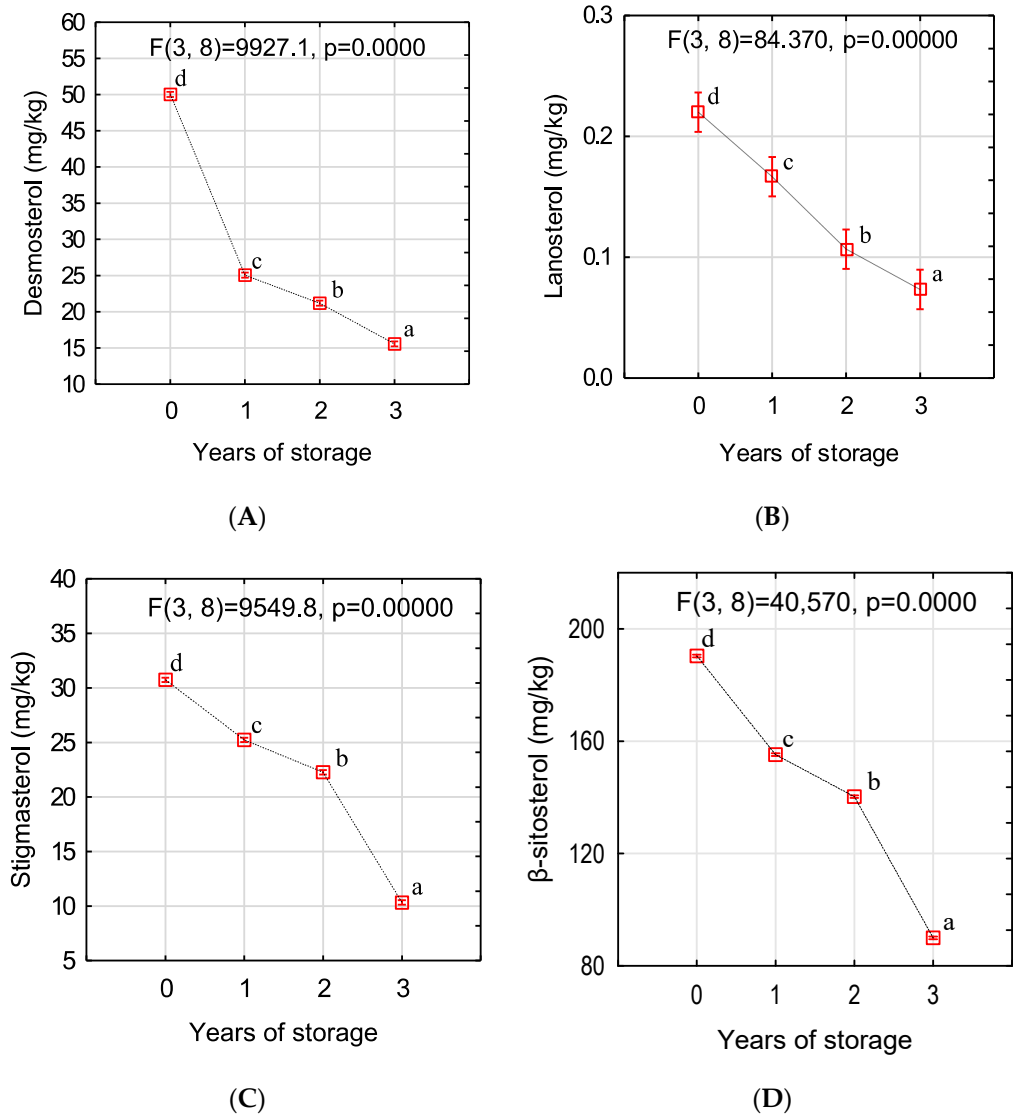


Figure 6. Changes in the content of sterols: (**A**) desmosterol, (**B**) lanosterol, (**C**) stigmasterol and (**D**) β-sitosterol. (a–d letters indicate homogeneous groups).

Table 2 presents the results of the analysis of LMOWA content. These LMOWAs are characterized by the possession of at least one carboxyl group which can derive from the plant root exudates, decomposition of soil matter, microorganisms metabolites, etc. [65]. The results showed that for each of the analyzed acids, a significant increase in concentration was observed during storage. The total LMOWA content in logging residues increased by approx. 225% after three years of storage. Similar to the increasing ergosterol content, this increase can be related to the growth of fungi. Plassard and Fransson [66] stated that,

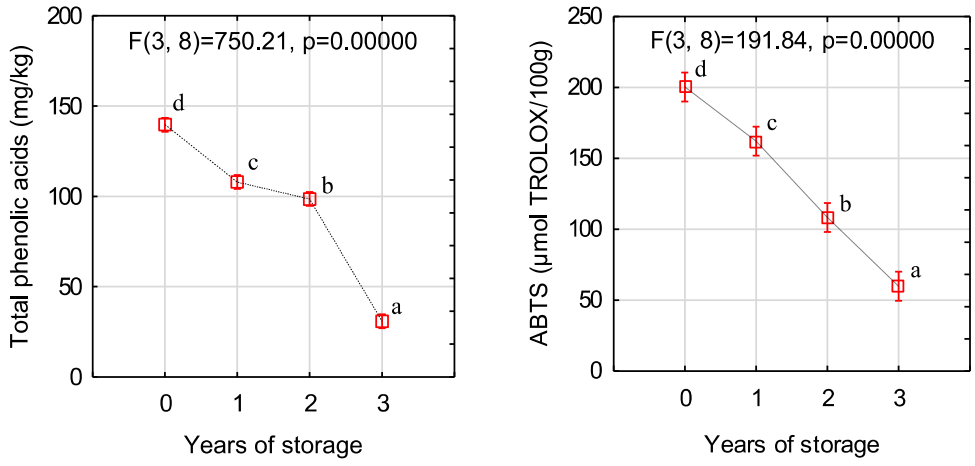
in biotechnology, citric and oxalic acids have, in recent years, attracted the most attention as fungal metabolites. Moreover, these acids were previously used as a bio-indicators of the wood chip infestation with mold fungi during storage [47]. The enzymatic formation of oxalic acids by brown-rot and white-rot fungi has also been previously described [67]. Additionally, other LMOWAs such as malic, malonic, formic, fumaric and acetic acids have also been reported as the products of fungal growth [68–72]. According to Plassard and Fransson [66], the central reaction in the production of LMOWAs is probably the fixation of a carbon dioxide of pyruvate by the action of pyruvate carboxylase to form oxaloacetate which can be further metabolized into the various types of LMOWAs. However, the progressive increase in the concentration of organic acids during storage is an unfavorable effect due to, for example, the increased enzymatic activity of fungi in the acidic environment [73].

Table 2. Changes in the concentration of low molecular weight organic acids. (a–d letters indicate homogeneous groups; the total acids content is marked in bold letters).

Type of Acid	Acid Concentration (μg/g)			
	0 Years	**1 Year**	**2 Years**	**3 Years**
Lactic	$0.11^{a} \pm 0.02$	$0.22^{b} \pm 0.01$	$0.82^{c} \pm 0.04$	$1.53^{d} \pm 0.08$
Acetic	$0.29^{a} \pm 0.06$	$0.79^{b} \pm 0.04$	$2.23^{c} \pm 0.03$	$8.16^{d} \pm 0.03$
Malonic	$9.36^{a} \pm 0.03$	$15.39^{b} \pm 0.09$	$16.55^{c} \pm 0.02$	$32.51^{d} \pm 0.06$
Maleic	$20.33^{a} \pm 0.08$	$23.22^{b} \pm 0.07$	$38.24^{c} \pm 0.05$	$70.24^{d} \pm 0.08$
Formic	$5.25^{a} \pm 0.05$	$6.11^{b} \pm 0.04$	$6.37^{c} \pm 0.07$	$7.05^{d} \pm 0.03$
Oxalic	$5.11^{a} \pm 0.09$	$40.36^{b} \pm 0.11$	$50.74^{c} \pm 0.14$	$89.35^{d} \pm 0.17$
Malic	$10.25^{a} \pm 0.04$	$50.33^{b} \pm 0.12$	$78.52^{c} \pm 0.16$	$198.33^{d} \pm 0.09$
Citric	$152.31^{a} \pm 0.09$	$155.70^{b} \pm 0.04$	$159.71^{c} \pm 0.06$	$161.44^{d} \pm 0.04$
Succinic	$1.32^{a} \pm 0.05$	$10.22^{b} \pm 0.03$	$11.36^{c} \pm 0.04$	$21.35^{d} \pm 0.08$
Fumaric	$10.06^{a} \pm 0.07$	$30.06^{b} \pm 0.06$	$48.22^{c} \pm 0.05$	$106.52^{d} \pm 0.07$
Sum	**214.39**	**332.40**	**412.76**	**696.48**

As shown in Figure 7A, the total phenolic acid content decreased during storage. These phenolic acids are compounds that contain hydroxyl and carboxyl groups in their structure. Other phenolic acid complexes such as complexes with fatty acids, flavonoids, sterols and structural polymers of cell walls are also common in plant tissue. Moreover, there is also a separate group composed of depsides which are a complex of at least two molecules of phenolic acids. The most frequently identified phenolic acids in Scots pine include caffeic, salicylic, ferulic, vanillic, gallic, p-coumaric and protocatechuic acids [74]. During the three-year storage period, the total content of phenolic acids in the residues decreased by 76%. This effect can also be attributed to the significant activity of fungi commonly found in the forest environments such as white-rot fungi, brown-rot fungi, ectomycorrhizal fungi and ericoid mycorrhizal fungi, which show the ability to degrade the phenolic compounds [75–77].

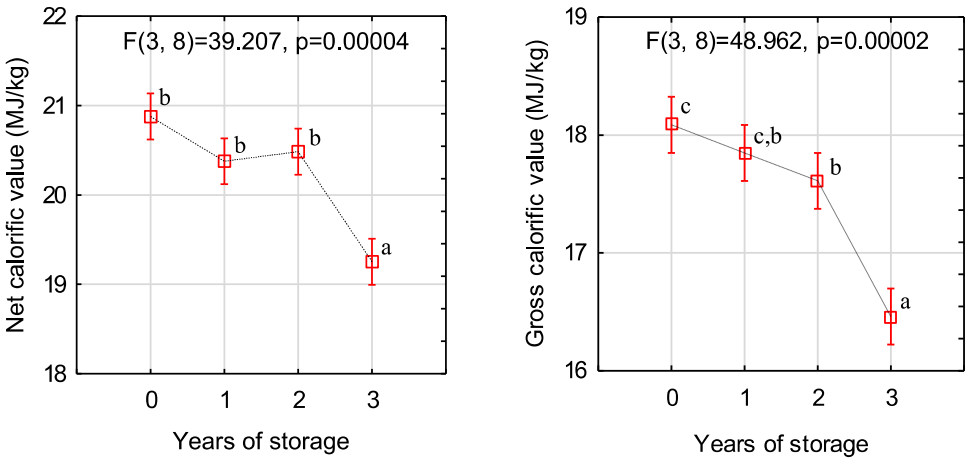
Figure 7B presents the results of the antioxidant activity analysis. Based on the outcomes, it was found that the antioxidant activity of wood residues, determined by the $ABTS^{\cdot+}$ method, decreased with storage time by up to 66%. Taking into account the fact that that the antioxidant activity of plant tissue is correlated with the total phenolics content, the observed reduction may have been related to a decrease in total phenolic acids which, as mentioned before, can be caused by the activity of various types of fungi [78,79].



(**A**) (**B**)

Figure 7. Changes in: (**A**) total phenolic acids content and (**B**) antioxidant activity. (a–d letters indicate homogeneous groups).

The results of net calorific value and gross calorific value are presented in Figures 8A and 8B, respectively. These parameters are used to determine the energy potential of various types of fuels. Gross calorific value (GCV) is an indicator of an amount of heat released during total combustion in an oxygen environment when the created water is in a liquid state, while in the case of net calorific value (NCV) it is in a vapor state [80]. Based on these outcomes, it was found that the only statistically significant difference in NCVs occurred after three years of storage, so no significant changes were noticed during the first two years of storage. On the other hand, GCV values showed a significant reduction in the amount of heat that had already been released in the second year of storage. Considering that the caloric value of wood is closely related to its chemical composition, it can be assumed that the activity of fungi and abiotic factors, which most likely contributed to the reduction in the cellulose content, also contributed to a reduction in the caloric value of the residues [81,82].



(**A**) (**B**)

Figure 8. Changes in: (**A**) net calorific value and (**B**) gross calorific value. (a–c letters indicate homogeneous groups).

Table 3 presents the results of ash content determinations. It was found that as the storage period increased, the ash content also significantly increased. This effect is consistent with previous studies which showed a negative correlation between the calorific

value and ash content [83]. This is a negative effect considering that the presence of ash adversely affects woodchip quality and combustion efficiency and can cause various problems related to cleaning of devices and combustion [84].

Table 3. Changes in the ash content during storage. (a–d letters indicate homogeneous groups).

Ash Content (%)			
0 Years	**1 Year**	**2 Years**	**3 Years**
0.65 ^{a} ± 0.05	0.86 ^{b} ± 0.08	2.34 ^{c} ± 0.53	4.17 ^{d} ± 0.99

4. Conclusions

Based on the performed investigations, it can be concluded that storing the pine logging residues in a forest site for a period of three years causes significant changes in their properties. Most of the changes that occurred were the result of the activity of microorganisms such as fungi or bacteria. After three years of storage, wood is characterized by a much lower cellulose content and, consequently, an increased percentage share of lignin. Moreover, a much higher concentration of ergosterol was also found in the case of stored material, which indicates high fungal infestation. The concentration of the remaining analyzed sterols (desmosterol, stigmasterol, lanosterol and β-sitosterol) decreased significantly, as did the total phenolic acid content and antioxidant activity. On the other hand, the concentration of low molecular weight organic acids increased, which may also indicate fungal activity. Furthermore, the three-year storage period resulted in a reduction in the energy potential of the residues, as shown by the reduction in net and gross calorific value and the increased ash content. The shorter periods of storage of forest biomass contributes to a slight decrease in its calorific value. The acceptable level of unprotected storage of forest biomass, as an alternative solid fuel, should not exceed the indicated period of one to two years.

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References

1. Shmulsky, R.; Jones, P.D. *Forest Products and Wood Science: An Introduction*; John Wiley & Sons: New York, NY, USA, 2019; ISBN 9780813820743.
2. Wieruszewski, M.; Turbański, W.; Mydlarz, K.; Sydor, M. Economic Efficiency of Pine Wood Processing in Furniture Production. *Forests* **2023**, *14*, 688. [CrossRef]
3. Ranius, T.; Hämäläinen, A.; Egnell, G.; Olsson, B.; Eklöf, K.; Stendahl, J.; Rudolphi, J.; Sténs, A.; Felton, A. The Effects of Logging Residue Extraction for Energy on Ecosystem Services and Biodiversity: A Synthesis. *J. Environ. Manag.* **2018**, *209*, 409–425. [CrossRef]
4. Amiandamhen, S.O.; Kumar, A.; Adamopoulos, S.; Jones, D.; Nilsson, B. Bioenergy Production and Utilization in Different Sectors in Sweden: A State of the Art Review. *BioResources* **2020**, *15*, 9834. [CrossRef]
5. Bessaad, A.; Bilger, I.; Korboulewsky, N. Assessing Biomass Removal and Woody Debris in Whole-Tree Harvesting System: Are the Recommended Levels of Residues Ensured? *Forests* **2021**, *12*, 807. [CrossRef]
6. Ghaffariyan, M.R. Remaining Slash in Different Harvesting Operation Sites in Australian Plantations. *Silva Balc.* **2013**, *14*, 83–93.
7. Ghaffariyan, M.R.; Acuna, M.; Wiedemann, J.; Mitchell, R. *Productivity of the Bruks Chipper When Harvesting Forest Biomass in Pine Plantations*; CRC for Forestry Bulletin 16; CRC Press: Boca Raton, FL, USA, 2011.

8. Conway, S. *Logging Practices: Principles of Timber Harvesting Systems, Revised ed.*; Miller Freeman Inc.: San Francisco, CA, USA, 1982.
9. Watson, W.F.; Stokes, B.J.; Savelle, I.W. Comparisons of Two Methods of Harvesting Biomass for Energy. *For. Prod. J.* **1986**, *36*, 63–68.
10. Spinelli, R.; Visser, R.; Björheden, R.; Röser, D. Recovering Energy Biomass in Conventional Forest Operations: A Review of Integrated Harvesting Systems. *Curr. For. Rep.* **2019**, *5*, 90–100. [CrossRef]
11. Cuchet, E.; Roux, P.; Spinelli, R. Performance of a Logging Residue Bundler in the Temperate Forests of France. *Biomass Bioenergy* **2004**, *27*, 31–39. [CrossRef]
12. Spinelli, R.; Lombardini, C.; Magagnotti, N. The Effect of Mechanization Level and Harvesting System on the Thinning Cost of Mediterranean Softwood Plantations. *Silva Fenn.* **2014**, *48*, 1003. [CrossRef]
13. Hytönen, J.; Moilanen, M. Effect of Harvesting Method on the Amount of Logging Residues in the Thinning of Scots Pine Stands. *Biomass Bioenergy* **2014**, *67*, 347–353. [CrossRef]
14. Ghaffariyan, M.R.; Apolit, R. Harvest Residues Assessment in Pine Plantations Harvested by Whole Tree and Cut-to-Length Harvesting Methods (a Case Study in Queensland, Australia). *Silva Balc.* **2015**, *16*, 113–122.
15. Koelling, C.; Göttlein, A.; Rothe, A. Energieholz Nachhaltig Nutzen–Biomassenutzung Und Nährstoffentzug. *LWF Aktuell* **2007**, 32–36.
16. Beardsell, M.G. *Integrated Harvesting Systems to Incorporate the Recovery of Logging Residues with the Harvesting of Conventional Forest Products*; Virginia Polytechnic Institute and State University: Blacksburg, VA, USA, 1983.
17. Nurmi, J.; Hillebrand, K. Storage Alternatives Affect Fuelwood Properties of Norway Spruce Logging Residues. *N. Z. J. For. Sci.* **2001**, *31*, 289–297.
18. Zyryanov, M.; Medvedev, S.; Mokhirev, A. Study of the Possibility of Using Logging Residue for the Production of Wood Processing Enterprises. *J. Appl. Eng. Sci.* **2020**, *18*, 15–18. [CrossRef]
19. Schnepf, C.; Graham, R.T.; Kegley, S.; Jain, T.B. *Managing Organic Debris for Forest Health*; Pacific Northwest Extension Publication PNW, PNW609; Washington State University: Pullman, WA, USA, 2009.
20. Smolander, A.; Saarsalmi, A.; Tamminen, P. Response of Soil Nutrient Content, Organic Matter Characteristics and Growth of Pine and Spruce Seedlings to Logging Residues. *For. Ecol. Manag.* **2015**, *357*, 117–125. [CrossRef]
21. Richardson, J.; Björheden, R.; Hakkila, P.; Lowe, A.T.; Smith, C.T. *Bioenergy from Sustainable Forestry: Guiding Principles and Practice*; Springer: Berlin, Germany, 2002.
22. Mälkönen, E. Effect of Whole-Tree Harvesting on Soil Fertility. *Silva Fenn* **1976**, *10*, 157–164. [CrossRef]
23. Evans, A.M. *Ecology of Dead Wood in the Southeast*; Forest Guild: Santa Fe, NM, USA, 2011; p. 37.
24. Hakkila, P. *Operations with Reduced Environmental Impact*; Klewer Academic Publishers: Dordrecht, The Netherlands, 2002; pp. 244–261.
25. Wall, A.; Hytönen, J. The Long-Term Effects of Logging Residue Removal on Forest Floor Nutrient Capital, Foliar Chemistry and Growth of a Norway Spruce Stand. *Biomass Bioenergy* **2011**, *35*, 3328–3334. [CrossRef]
26. Achat, D.L.; Deleuze, C.; Landmann, G.; Pousse, N.; Ranger, J.; Augusto, L. Quantifying Consequences of Removing Harvesting Residues on Forest Soils and Tree Growth–A Meta-Analysis. *For. Ecol. Manag.* **2015**, *348*, 124–141. [CrossRef]
27. Kuiper, L.; Oldenburger, J. The Harvest of Forest Residues in Europe. In *Quick-Scans on Upstream Biomass: Yearbook*; Wageningen University & Research: Wageningen, The Netherlands, 2006; pp. 13–18.
28. Thiffault, E.; Béchard, A.; Paré, D.; Allen, D. Recovery Rate of Harvest Residues for Bioenergy in Boreal and Temperate Forests: A Review. In *Advances in Bioenergy: The Sustainability Challenge*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2016; pp. 293–316.
29. Titus, B.D.; Brown, K.; Helmisaari, H.-S.; Vanguelova, E.; Stupak, I.; Evans, A.; Clarke, N.; Guidi, C.; Bruckman, V.J.; Varnagiryte-Kabasinskiene, I. Sustainable Forest Biomass: A Review of Current Residue Harvesting Guidelines. *Energy Sustain. Soc.* **2021**, *11*, 1–32. [CrossRef]
30. Malinowski, Z.; Kawalerczyk, J.; Walkiewicz, J.; Dziurka, D.; Mirski, R. The Effect of the Tree Dieback Process on the Mechanical Properties of Pine (*Pinus sylvestris* L.) Wood. *Forests* **2023**, *14*, 274. [CrossRef]
31. Bekhta, P.; Kozak, R.; Gryc, V.; Sebera, V.; Tippner, J. Effects of Wood Particles from Deadwood on the Properties and Formaldehyde Emission of Particleboards. *Polymers* **2022**, *14*, 3535. [CrossRef]
32. Lebreton, A.; Zeng, Q.; Miyauchi, S.; Kohler, A.; Dai, Y.-C.; Martin, F.M. Evolution of the Mode of Nutrition in Symbiotic and Saprotrophic Fungi in Forest Ecosystems. *Annu. Rev. Ecol. Evol. Syst.* **2021**, *52*, 385–404. [CrossRef]
33. Liu, S.; Wang, H.; Tian, P.; Yao, X.; Sun, H.; Wang, Q.; Delgado-Baquerizo, M. Decoupled Diversity Patterns in Bacteria and Fungi across Continental Forest Ecosystems. *Soil Biol. Biochem.* **2020**, *144*, 107763. [CrossRef]
34. Available online: www.lasy.gov.pl (accessed on 30 June 2023).
35. Ghaffariyan, M.R.; Spinelli, R.; Magagnotti, N.; Brown, M. Integrated Harvesting for Conventional Log and Energy Wood Assortments: A Case Study in a Pine Plantation in Western Australia. *South. For. J. For. Sci.* **2015**, *77*, 249–254. [CrossRef]
36. Smethurst, P.J.; Nambiar, E.K.S. Distribution of Carbon and Nutrients and Fluxes of Mineral Nitrogen after Clear-Felling a Pinus Radiata Plantation. *Can. J. For. Res.* **1990**, *20*, 1490–1497. [CrossRef]
37. Palacka, M.; Vician, P.; Holubčík, M.; Jandačka, J. The Energy Characteristics of Different Parts of the Tree. *Procedia Eng.* **2017**, *192*, 654–658. [CrossRef]

38. Singh, T.; Kostecky, M.M. Calorific Value Variations in Components of 10 Canadian Tree Species. *Can. J. For. Res.* **1986**, *16*, 1378–1381. [CrossRef]
39. Miao, Z.; Grift, T.E.; Hansen, A.C.; Ting, K.C. Energy Requirement for Comminution of Biomass in Relation to Particle Physical Properties. *Ind. Crops Prod.* **2011**, *33*, 504–513. [CrossRef]
40. Jewiarz, M.; Wróbel, M.; Mudryk, K.; Szufa, S. Impact of the Drying Temperature and Grinding Technique on Biomass Grindability. *Energies* **2020**, *13*, 3392. [CrossRef]
41. *T264-cm-07*; Preparation of Wood for Chemical Analysis. Technical Association of the Pulp and Paper Industry: New York, NY, USA, 2001.
42. Browning, B.L. *The Chemistry of Wood*; Interscience: Geneva, Switzerland, 1963.
43. *T 222 cm-06*; Acid Insoluble Lignin in Wood and Pulp. Technical Association of the Pulp and Paper Industry: New York, NY, USA, 2006; p. 5.
44. Szwajkowska-Michałek, L.; Rogoziński, T.; Mirski, R.; Stuper-Szablewska, K. Wood Processing Waste–Contamination with Microscopic Fungi and Contents of Selected Bioactive Compounds. *BioResources* **2020**, *15*, 1763–1772. [CrossRef]
45. Stuper-Szablewska, K.; Rogoziński, T.; Perkowski, J. Contamination of Pine and Birch Wood Dust with Microscopic Fungi and Determination of Its Sterol Contents. *Arh. Hig. Rada Toksikol.* **2017**, *68*, 127. [CrossRef] [PubMed]
46. Stuper-Szablewska, K.; Szablewski, T.; Przybylska-Balcerek, A.; Szwajkowska-Michałek, L.; Krzyżaniak, M.; Świerk, D.; Cegielska-Radziejewska, R.; Krejpcio, Z. Antimicrobial Activities Evaluation and Phytochemical Screening of Some Selected Plant Materials Used in Traditional Medicine. *Molecules* **2023**, *28*, 244. [CrossRef] [PubMed]
47. Mirski, R.; Kawalerczyk, J.; Dziurka, D.; Stuper-Szablewska, K.; Wieruszewski, M. Mold Fungi Development during the Short-Term Wood-Chips Storage Depending on the Storage Method. *Wood Mater. Sci. Eng.* **2023**, *18*, 1243–1251. [CrossRef]
48. Re, R.; Pellegrini, N.; Proteggente, A.; Pannala, A.; Yang, M.; Rice-Evans, C. Antioxidant Activity Applying an Improved ABTS Radical Cation Decolorization Assay. *Free Radic. Biol. Med.* **1999**, *26*, 1231–1237. [CrossRef] [PubMed]
49. *STN ISO 1928*; Solid Mineral Fuels—Determination of Gross Calorific Value by the Bomb Calorimetric Method, and Calculation of Net Calorific Value. European Committee for Standardization (CEN-CENELEC): Brussels, Belgium, 2003.
50. *EN ISO 18122*; Solid Biofuels: Determination of Ash Content. European Committee for Standardization (CEN-CENELEC): Brussels, Belgium, 2016.
51. Jakob, M.; Mahendran, A.R.; Gindl-Altmutter, W.; Bliem, P.; Konnerth, J.; Mueller, U.; Veigel, S. The Strength and Stiffness of Oriented Wood and Cellulose-Fibre Materials: A Review. *Prog. Mater. Sci.* **2022**, *125*, 100916. [CrossRef]
52. Rodriguez-Fabia, S.; Torstensen, J.; Johansson, L.; Syverud, K. Hydrophobisation of Lignocellulosic Materials Part I: Physical Modification. *Cellulose* **2022**, *29*, 5375–5393. [CrossRef]
53. Tripathi, S.; Mishra, O.P.; Gangwar, A.; Chakrabarti, S.K.; Varadhan, R. Impact of Wood Storage on Pulp and Paper Making Properties. *IPPTA J.* **2011**, *23*, 161–164.
54. Chang, S.-T. *Photodegradation and Photoprotection of Wood Surfaces*; US Forest Products Laboratory: Madison, WI, USA, 1982.
55. Alakoski, E.; Jämsén, M.; Agar, D.; Tampio, E.; Wihersaari, M. From Wood Pellets to Wood Chips, Risks of Degradation and Emissions from the Storage of Woody Biomass—A Short Review. *Renew. Sustain. Energy Rev.* **2016**, *54*, 376–383. [CrossRef]
56. Przybysz Buzała, K.; Kalinowska, H.; Małachowska, E.; Boruszewski, P.; Krajewski, K.; Przybysz, P. The Effect of Lignin Content in Birch and Beech Kraft Cellulosic Pulps on Simple Sugar Yields from the Enzymatic Hydrolysis of Cellulose. *Energies* **2019**, *12*, 2952. [CrossRef]
57. Täubel, M.; Jalanka, J.; Kirjavainen, P.V.; Tuoresmäki, P.; Hyvärinen, A.; Skevaki, C.; Piippo-Savolainen, E.; Pekkanen, J.; Karvonen, A.M. Fungi in Early-Life House Dust Samples and the Development of Asthma: A Birth Cohort Study. *Ann. Am. Thorac. Soc.* **2023**, *20*, 1456–1464. [CrossRef]
58. Mirski, R.; Kawalerczyk, J.; Dziurka, D.; Stuper-Szablewska, K.; Walkiewicz, J. Selected Chemical and Physical Properties of Pine Wood Chips Inoculated with Aspergillus and Penicillium Mold Fungi. *Drv. Ind.* **2023**, *74*, 317–326. [CrossRef]
59. Gutarowska, B.; Cichocka, A. Zastosowanie Metody Oznaczania Ergosterolu Do Szybkiej Oceny Zanieczyszczenia Grzybami Na Różnych Etapach Produkcji Papieru. *Przegląd Papierniczy* **2010**, *66*, 45–47.
60. Leppänen, H.K.; Nevalainen, A.; Vepsäläinen, A.; Roponen, M.; Täubel, M.; Laine, O.; Rantakokko, P.; Von Mutius, E.; Pekkanen, J.; Hyvärinen, A. Determinants, Reproducibility, and Seasonal Variation of Ergosterol Levels in House Dust. *Indoor Air* **2014**, *24*, 248–259. [CrossRef]
61. Pasanen, A.-L.; Yli-Pietilä, K.; Pasanen, P.; Kalliokoski, P.; Tarhanen, J. Ergosterol Content in Various Fungal Species and Biocontaminated Building Materials. *Appl. Environ. Microbiol.* **1999**, *65*, 138–142. [CrossRef] [PubMed]
62. Rogoziński, T.; Szwajkowska-Michałek, L.; Matysiak, A.; Stuper-Szablewska, K. The content of bioactive compounds in chips from the wood processing line. *Chip Chipless Woodwork. Process.* **2018**, *11*, 145–150.
63. Rogowska, A.; Szakiel, A. The Role of Sterols in Plant Response to Abiotic Stress. *Phytochem. Rev.* **2020**, *19*, 1525–1538. [CrossRef]
64. Gutiérrez, A.; Del Rio, J.C.; Martínez-Íñigo, M.J.; Martínez, M.J.; Martínez, Á.T. Production of New Unsaturated Lipids during Wood Decay by Ligninolytic Basidiomycetes. *Appl. Environ. Microbiol.* **2002**, *68*, 1344–1350. [CrossRef]
65. Chen, H.; Dou, J.; Xu, H. The Effect of Low-Molecular-Weight Organic-Acids (LMWOAs) on Treatment of Chromium-Contaminated Soils by Compost-Phytoremediation: Kinetics of the Chromium Release and Fractionation. *J. Environ. Sci.* **2018**, *70*, 45–53. [CrossRef]

66. Plassard, C.; Fransson, P. Regulation of Low-Molecular Weight Organic Acid Production in Fungi. *Fungal Biol. Rev.* **2009**, *23*, 30–39. [CrossRef]
67. Shimada, M.; Akamtsu, Y.; Tokimatsu, T.; Mii, K.; Hattori, T. Possible Biochemical Roles of Oxalic Acid as a Low Molecular Weight Compound Involved in Brown-Rot and White-Rot Wood Decays. *J. Biotechnol.* **1997**, *53*, 103–113. [CrossRef]
68. Johansson, E.M.; Fransson, P.M.; Finlay, R.D.; van Hees, P.A. Quantitative Analysis of Root and Ectomycorrhizal Exudates as a Response to Pb, Cd and As Stress. *Plant Soil* **2008**, *313*, 39–54. [CrossRef]
69. Takao, S. Organic Acid Production by Basidiomycetes: I. Screening of Acid-Producing Strains. *Appl. Microbiol.* **1965**, *13*, 732–737. [CrossRef]
70. Mäkelä, M.; Galkin, S.; Hatakka, A.; Lundell, T. Production of Organic Acids and Oxalate Decarboxylase in Lignin-Degrading White Rot Fungi. *Enzym. Microb. Technol.* **2002**, *30*, 542–549. [CrossRef]
71. Hofrichter, M.; Vares, T.; Kalsi, M.; Galkin, S.; Scheibner, K.; Fritsche, W.; Hatakka, A. Production of Manganese Peroxidase and Organic Acids and Mineralization of 14C-Labelled Lignin (14C-DHP) during Solid-State Fermentation of Wheat Straw with the White Rot Fungus Nematoloma Frowardii. *Appl. Environ. Microbiol.* **1999**, *65*, 1864–1870. [CrossRef]
72. Galkin, S.; Vares, T.; Kalsi, M.; Hatakka, A. Production of Organic Acids by Different White-Rot Fungi as Detected Using Capillary Zone Electrophoresis. *Biotechnol. Tech.* **1998**, *12*, 267–271. [CrossRef]
73. Mansour, M.M.; Hamed, S.A.E.-K.M.; Salem, M.Z.; Ali, H.M. Illustration of the Effects of Five Fungi on Acacia Saligna Wood Organic Acids and Ultrastructure Alterations in Wood Cell Walls by HPLC and TEM Examinations. *Appl. Sci.* **2020**, *10*, 2886. [CrossRef]
74. Szwajkowska-Michałek, L.; Przybylska-Balcerek, A.; Rogoziński, T.; Stuper-Szablewska, K. Phenolic Compounds in Trees and Shrubs of Central Europe. *Appl. Sci.* **2020**, *10*, 6907. [CrossRef]
75. Bending, G.D.; Read, D.J. Lignin and Soluble Phenolic Degradation by Ectomycorrhizal and Ericoid Mycorrhizal Fungi. *Mycol. Res.* **1997**, *101*, 1348–1354. [CrossRef]
76. Di Lella, S.; La Porta, N.; Tognetti, R.; Lombardi, F.; Nardin, T.; Larcher, R. White Rot Fungal Impact on the Evolution of Simple Phenols during Decay of Silver Fir Wood by UHPLC-HQOMS. *Phytochem. Anal.* **2022**, *33*, 170–183. [CrossRef] [PubMed]
77. Goodell, B.; Jellison, J.; Liu, J.; Daniel, G.; Paszczynski, A.; Fekete, F.; Krishnamurthy, S.; Jun, L.; Xu, G. Low Molecular Weight Chelators and Phenolic Compounds Isolated from Wood Decay Fungi and Their Role in the Fungal Biodegradation of Wood. *J. Biotechnol.* **1997**, *53*, 133–162. [CrossRef]
78. Diouf, P.-N.; Merlin, A.; Perrin, D. Antioxidant Properties of Wood Extracts and Colour Stability of Woods. *Ann. For. Sci.* **2006**, *63*, 525–534. [CrossRef]
79. Antoniewicz, J.; Kochman, J.; Jakubczyk, K.; Janda-Milczarek, K. The Influence of Time and Storage Conditions on the Antioxidant Potential and Total Phenolic Content in Homemade Grape Vinegars. *Molecules* **2021**, *26*, 7616. [CrossRef] [PubMed]
80. Orémusová, E.; Tereňová, L.; Réh, R. Evaluation of the Gross and Net Calorific Value of the Selected Wood Species. In *Proceedings of the Advanced Materials Research*; Trans Tech Publishers: Zurich, Switzerland, 2014; Volume 1001, pp. 292–299.
81. Gendek, A.; Piętka, J.; Aniszewska, M.; Malaťák, J.; Velebil, J.; Tamelová, B.; Krilek, J.; Moskalik, T. Energy Value of Silver Fir (*Abies Alba*) and Norway Spruce (*Picea Abies*) Wood Depending on the Degree of Its Decomposition by Selected Fungal Species. *Renew. Energy* **2023**, *215*, 118948. [CrossRef]
82. Domingos, I.; Ayata, U.; Ferreira, J.; Cruz-Lopes, L.; Sen, A.; Sahin, S.; Esteves, B. Calorific Power Improvement of Wood by Heat Treatment and Its Relation to Chemical Composition. *Energies* **2020**, *13*, 5322. [CrossRef]
83. Lieskovský, M.; Jankovský, M.; Trenčiansky, M.; Merganič, J. Ash Content vs. the Economics of Using Wood Chips for Energy: Model Based on Data from Central Europe. *BioResources* **2017**, *12*, 1579–1592. [CrossRef]
84. Mancini, M.; Rinnan, Å.; Pizzi, A.; Toscano, G. Prediction of Gross Calorific Value and Ash Content of Woodchip Samples by Means of FT-NIR Spectroscopy. *Fuel Process. Technol.* **2018**, *169*, 77–83. [CrossRef]

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