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Effects of microwave irradiation on the moisture content of various wood chip fractions obtained from different tree species

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Abstract

The paper proposes the use of microwave irradiation to lower the initial moisture content of wood chips. The study involved willow and fir chips fractionated by means of a sieve separator and unfractionated ash chips. The wood chips were exposed to a constant microwave power of 800 W for 30 s, 60 s, 120 s and 180 s. The chips were weighed before and after irradiation to measure loss of moisture. It was found that the decline in moisture content increased with wood chip size for a given irradiation time and microwave power. The initial moisture content of wood chips was not found to significantly affect loss of moisture as the drying rates of wood chips with higher and lower moisture content exposed to microwaves were not statistically different. The results showed that irradiation intensity increased with the time of exposure to microwaves and unit radiant energy per unit of evaporated moisture decreased with increasing wood chip size in the 3.15–31.50 mm range.

Keywords: Wood chips, Microwaves, Separation, Thermal imaging

Introduction

Wood chips may be generated at the harvest site, at a nearby landing, or at the plant where they are to be utilized [1]. Their shape should approximate a parallelepiped and their size should be precisely defined with respect to their intended purpose. The quality of wood chips is evaluated using the following criteria [2]: the degree of compliance of the desired fraction chips dimensions with the designated range, the percentage share of particular size fractions, the percentage share of bark, and the quantity of mechanical surface defects. Technical requirements vary between wood chips for defibration, for pulp and paper, for fiberboards, etc. Wood chips used for these applications are sorted as the various fractions may differ in moisture content.

Storing wood chips when raw material parameters and storage conditions are unfavorable may have negative effects on their quality. Due to the increased microbiological activity of the raw material, which results in loss of dry matter, greenhouse gas emissions (CH_4 , N_2O) and heating of the heap, in extreme cases the quality of the chips may significantly decrease, and in some cases even self-ignition may occur [3]. When storing large amounts of wood chips, it is very often necessary to reduce the water content from 60–90 to less than 40% if they will be transported, or to a level below 25%, in order to enable efficient burning or using wood chips as raw materials for production [4, 5].

The solutions for drying wood chips differ in technical aspects, however, the moisture reduction process is based on the diffusion of water in the particles of the material. The results of research to date clearly indicate that the diffusion coefficient depends, inter alia, on the geometry of the dried particles as well as on the temperature of the process [6–8]. Therefore, chip dryers are prevalently designed to dry particles called sawdust

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(<10 mm) and wood chips (<45 mm). The efficiency of these devices depends to the greatest extent on the initial and expected moisture content of the raw material and on its type (softwood, hard wood, straw material, etc.) as well as on the particle size [9]. Thus, in conventional drying, the kinetics of the drying process of larger particles are slower and the drying costs increases.

In the electromagnetic spectrum, microwaves, which are invisible to the human eye, are located between radio frequencies and infrared radiation. Within the microwave spectrum itself, only several bands have been allocated for industrial, scientific, and medical applications by the Federal Communications Commission (the frequency used herein was 2.45 GHz). Microwaves are reflected by metals, but pass through electrically neutral materials such as glass, most plastics, ceramic materials, and paper. If absorbed, they generate heat in the absorbent. Two particularly important properties of microwaves are volumetric heating and reversed temperature gradients in the heated material [10–15]. Currently, microwaves are increasingly widely used in medicine [16], agriculture [17–23], food processing [24–28], and forestry [29, 30], as well as for germination quality improvement [31–35], soil disinfection [36], insect control [37, 38].

Issue of interest to us is the use of microwave radiation for wood drying and conditioning [39–46], drying and treatment of wood products [43, 45], attempts have been made to optimize the steam preheating process of wood chips [47]. An important issue is to increase the efficiency of energy biomass drying [41, 44, 48]. The most important incentive to use microwave radiation for drying is the significant reduction in process time. Phyto-sanitation may be an additional, beneficial effect of using microwave radiation to dry wood [49–52]. The process of generating particles (chips and shavings) for the manufacture of engineered wood products, including particle boards, consists of several stages, depending on board type. In the case of regular particle boards, the shavings must be dried and sorted (fractionated), as they vary widely in terms of their dimensions. This is important in the production of 3- and 5-layer boards, with fine and coarse shavings being used for the external and internal layers, respectively. On the other hand, the shavings used for oriented strand boards (OSB) [53] do not have to

be sorted. Therefore, the present paper describes microwave-induced changes in the moisture content of both fractionated material (willow and fir chips) and unfractionated material (ash chips).

Given the above, the present paper examined the effects of a short exposure to microwave irradiation on the moisture content of fractionated and unfractionated wood chips. The research question was whether a short exposure of wood chips of different sizes and tree species might significantly reduce their moisture content and whether they should be sorted prior to irradiation to improve drying process.

Materials and methods

The study material consisted of fresh wood chips produced in November 2018 from three tree species Ash chips (European ash *Fraxinus excelsior* L.) were obtained from tending cuts conducted in the city of Cracow (19° 55' E, 50° 01' N) using a Bandit 990XP chipper with an engine power of 85 hp, feed rate of 30 m min⁻¹, and a maximum feed diameter of 305 mm. Willow chips (white willow *Salix alba* L.) and fir chips (silver fir *Abies alba* Mill.) were generated from the trunks of 5- to 6-year-old trees in the town of Celestynów (21° 23' E, 52° 03' N) using a LS 150 DW track chipper with an engine power of 40 hp, feed rate of 12 m min⁻¹, and a maximum feed diameter of 150 mm. The material was taken from a 0.5-m³ pile of wood chips. Prior to testing, ash chips were stored at 21 °C and an air humidity of approx. 40% in a heated facility of the Department of Forest Work Mechanization, Institute of Forest Utilization and Forest Technology in Cracow, while willow and fir chips were kept in a ventilated hall of the Warsaw University of Life Sciences, in both cases for a period of 7 days.

The mean moisture content on dry basis of ash, willow, and fir chips amounted to 18.52%, 63.73%, and 99.73%, respectively (before starting measurements). In this paper, the moisture content is always referred to the dry matter. The moisture content of the chips was measured by the dryer-weight method [54]. Table 1 provides descriptive statistics for the studied wood chip species.

Ash chips were left unsorted, in contrast to willow and fir chips, which were fractionated using a sieve separator made by the company Łukomet (Poland) according

Table 1 Descriptive statistics for moisture content (%) of willow, fir, and ash chips

Species	Mean	Min.	Max.	Range	Variance	SD	CV
Willow	63.73	52.30	74.70	22.40	33.57	5.79	9.09
Fir	99.73	61.81	115.01	53.20	176.04	13.27	13.30
Ash	18.52	15.15	24.17	9.01	6.10	2.47	13.34

SD standard deviation, CV coefficient of variation

to the concept developed at the Department of Agricultural and Forestry Machinery, Warsaw University of Life Sciences, a patent application concerning the kinematics of sieve sets (P 386 476), and the standard ANSI/ASAE S424.1 MAR92 [55]. The separator sieves had round openings consistent with the standards [56] and [57]. The following sieve sizes were used: 63.0, 45.0, 31.5, 16.0, 8.0 and 3.15 mm. The sieve with the smallest openings was placed closest to the bottom of the separator [58]. Three 10 dm³ samples were taken from the study material, with an accuracy of 0.01 dm³, and placed on the top sieve. The separation time was 120 s after the device reached constant engine speed, and was measured using a stopwatch with an accuracy of 1 s. Following separation, the chips collected on each sieve were weighed using a WTC 3000 laboratory balance (RADWAG, Radom, Poland) to the nearest 0.1 g to determine the percentage share of the various fractions by weight.

The material collected from the various sieves was marked and placed in paper bags, which were then sealed. (The material was transported in hermetically sealed containers.) Subsequently, within 5 h, the material was transferred to the Institute of Forest Utilization and Forest Technology, University of Agriculture in Cracow. The wood chip fractions were divided into 150 g portions and placed in containers made of 0.4-mm-thick galvanized steel with internal dimensions of 140 × 190 × 70 mm and a weight of 386 g. Containers with wood chips were placed directly under a microwave horn antenna [36, 59] which was immobile during measurement. A diagram of the experimental stand is shown in Fig. 1.

The power output of the microwave emitter was 800 W, the aperture area of the horn antenna was 0.024254 m² (0.181 × 0.134 m), and the mean power density of microwaves was 33 kW m⁻². CADFEKO ver. 2.0.5 software was used to visualize the intensity distribution of the electromagnetic field emitted by the antenna (Fig. 2).

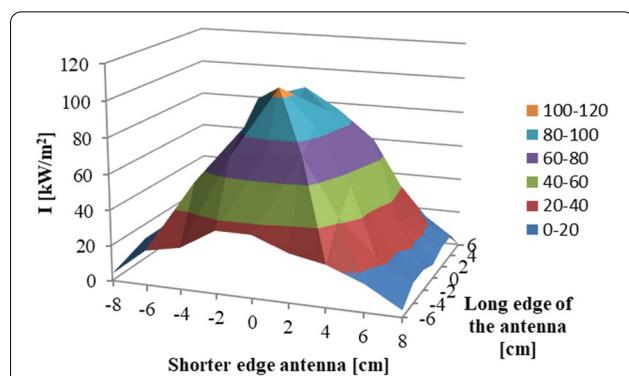
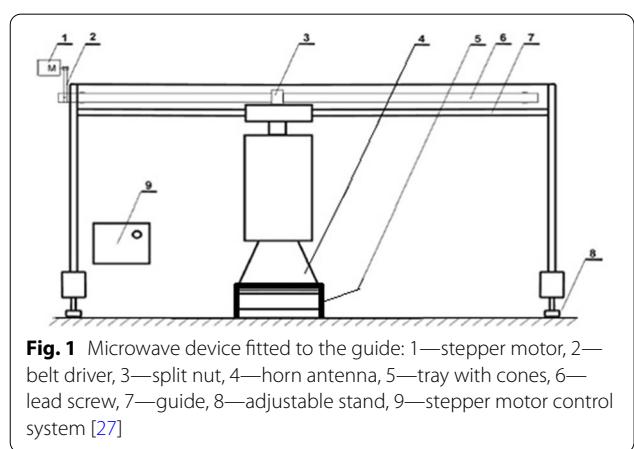


Fig. 2 Intensity distribution of the electromagnetic field under the horn antenna used in the study

The microwave irradiation time applied to the studied wood chip fractions were 30, 60, 120, and 180 s. Each variant was done in triplicate.

Immediately before and after irradiation, the container with wood chips was weighed on a laboratory balance (BTA2100D, AXIS, Poland) to measure loss of moisture. During the experiments, air humidity and temperature in the laboratory were recorded using a Voltcraft ST8820 multimeter with an accuracy of 0.1 °C and 0.1%, respectively.

Additionally, before and after microwave irradiation of ash chips, images were recorded using a thermal imaging camera (E64501, FLIR, Estonia). They were analyzed to obtain the temperature of wood chips at the designated time points.

Following microwave irradiation, the wood chips were transported to the Department of Agricultural and Forest Machinery, Warsaw University of Life Sciences, where they were desiccated to determine their dry weight and calculate moisture content using the oven-dry method for wood [54]. This procedure was conducted in a Heraeus UT 6120 circulating air oven (Kendro Laboratory Products GmbH, Hanau, Germany) at a constant temperature of 105 ± 2 °C for 24 h. The material was weighed using a WPS 600 laboratory balance (RADWAG, Radom, Poland) with an accuracy of 0.01 g.

Unit radiant flux (γ_p, γ_k), defined as the ratio of microwave power (P) to the weight of the material before (m_p) and after (m_k) irradiation, was calculated from Eqs. 1 and 2:

$$\gamma_p = \frac{P}{m_p} [\text{W g}^{-1}], \quad (1)$$

$$\gamma_k = \frac{P}{m_k} [\text{W g}^{-1}]. \quad (2)$$

In turn, unit radiant energy ε_u per loss of moisture ($m_u = m_p - m_k$) during processing was determined according to Eq. 3:

$$\varepsilon_u = \frac{P \times t}{m_u} [\text{J g}^{-1}], \quad (3)$$

where t is time in s.

Statistical analysis was done using Statistica 10 software for descriptive statistics and ANOVA (analysis of variance). The experiments were operationalized for analysis using two factors: fraction size and species of wood chips. Another analysis involved microwave irradiation time and species of wood chips. Statistical analysis was also used to evaluate loss of weight (moisture) after microwave irradiation. The normality of distribution of the studied factors was assessed by means of the Shapiro–Wilk test. Selected factors were compared using the Duncan test. All analyses were performed at a significance level of 0.05.

Results

Sieve analysis—size distribution of wood chips

Sieve separation revealed that the most abundant willow and fir fraction consisted of 8–16 mm wood chips (which passed through the 16-mm sieve and were retained by the 8-mm sieve), which accounted for more than $62.60 \pm 1.96\%$ and $48.96 \pm 0.77\%$ of the total material, respectively (Table 2). The second most abundant fraction consisted of 3.15–8.0 mm wood chips, accounting for $19.40 \pm 0.53\%$ and $33.17 \pm 1.72\%$ of total willow and fir chips, respectively. The forest wood chips used were fractionated fir and willow chips and unfractionated ash chips (Fig. 3).

The 63-mm sieve did not retain any wood chips, while the 45-mm sieve retained only 1.34% and 0.85% of willow



Fig. 3 Forest wood chips: **a** fractionated fir chips (<3.15; 3.15; 8.0; 16.0; 31.5 mm); **b** fractionated willow chips (<3.15; 3.15; 8.0; 16.0; 31.5; 45.0 mm); **c** unfractionated ash chips

and fir chips, respectively (Table 2 and Fig. 4). Thus, chips from those sieves were not included in further study due to their absence or negligible amount.

Table 2 Descriptive statistics for the percent distribution of willow and fir chips (by weight) between the various particle size categories

Species	Sieve size mm	Mean %	Min. %	Max. %	Range %	Variance	SD %	CV %
Willow	0–3.15	3.09	3.09	3.10	0.01	0.00	0.00	0.05
	3.15–8.0	19.40	19.02	19.77	0.75	0.28	0.53	2.74
	8.0–16.0	62.60	61.21	63.98	2.77	3.82	1.96	3.12
	16.0–31.50	11.09	9.37	12.80	3.44	5.90	2.43	21.92
	31.5–45.0	2.48	2.13	2.84	0.71	0.25	0.50	20.28
	45.0–63.0	1.34	0.99	1.70	0.71	0.25	0.50	37.54
Fir	0–3.15	5.49	5.10	5.87	0.77	0.30	0.55	9.95
	3.15–8.0	33.17	31.95	34.38	2.43	2.94	1.72	5.17
	8.0–16.0	48.96	48.41	49.50	1.09	0.59	0.77	1.57
	16.0–31.5	10.06	9.23	10.88	1.65	1.37	1.17	11.63
	31.5–45.0	1.48	1.17	1.79	0.62	0.19	0.44	29.39
	45.0–63.0	0.85	0.77	0.93	0.16	0.01	0.11	13.42

SD standard deviation, CV coefficient of variation

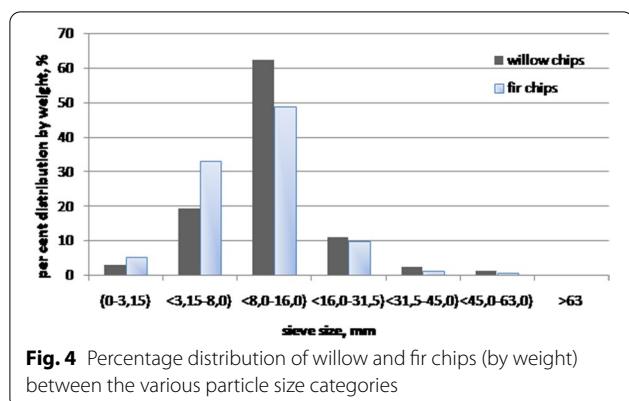


Fig. 4 Percentage distribution of willow and fir chips (by weight) between the various particle size categories

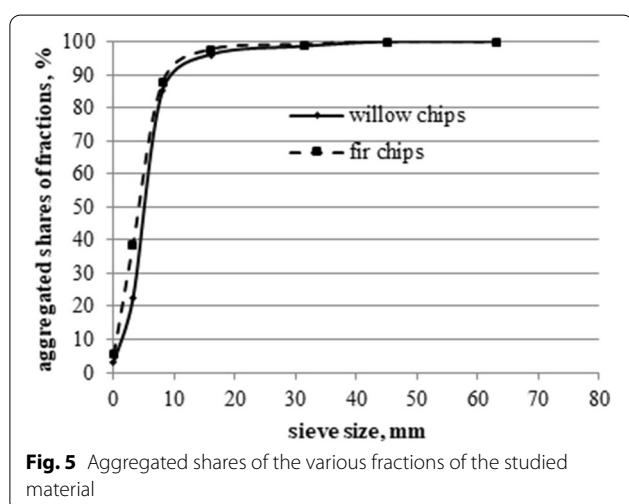


Fig. 5 Aggregated shares of the various fractions of the studied material

Wood chip size distributions were aggregated and plotted (by weight) for the studied wood chip species, as shown in Fig. 5. As can be seen, the shapes of the curves differ in the range between sieve sizes 3.15 mm to 8.0 mm.

Analysis of the moisture content of the various willow and fir wood chip fractions showed that it decreased with increasing particle size, with the exception of the <3.15 mm fraction, whose moisture content was similar to that of the 8 mm fraction (Table 3).

Effects of wood chip size on loss of moisture upon exposure to microwaves

The effects of microwaves were not studied for fractionated wood chips collected from sieves with 45 mm and 63 mm openings due to their absence or negligible amount. The results for the other size fractions are given in Table 4.

The study has shown that larger wood chips dried at a faster rate. Figures 6 and 7 present significant

Table 3 The average values of initial moisture content (%) for the considered fraction of willow and fir chips (before irradiation)

Species	Sieve size, mm	Time, s			
		30	60	120	180
Willow	0	–	69.25	68.37	–
	3.15	66.50	71.17	70.61	70.78
	8.0	64.25	64.03	63.85	62.35
	16.0	55.26	52.30	55.76	56.89
	31.5	–	–	53.60	–
	63	–	–	–	–
Fir	0	–	98.13	96.76	–
	3.15	113.00	112.37	110.67	111.12
	8.0	97.07	100.00	98.75	97.05
	16.0	80.83	79.76	76.29	72.63
	31.5	–	–	61.81	–
	63	–	–	–	–

The irradiation times were 30, 60, 120 and 180 s

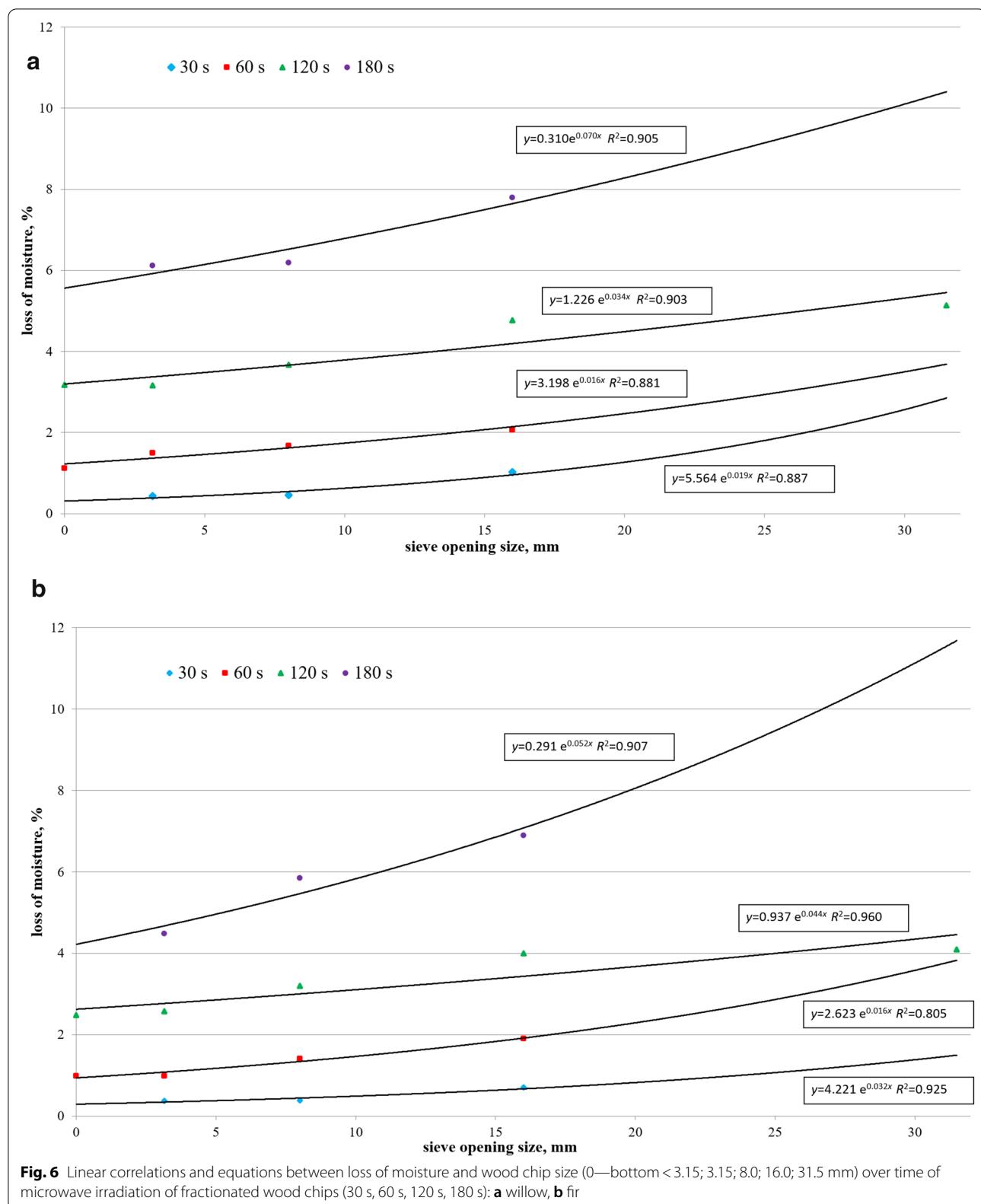
Table 4 Mean loss of moisture (as % of wood chip weight) in fractionated willow and fir chips after various microwave irradiation times (figures in brackets show those changes as % of initial moisture content)

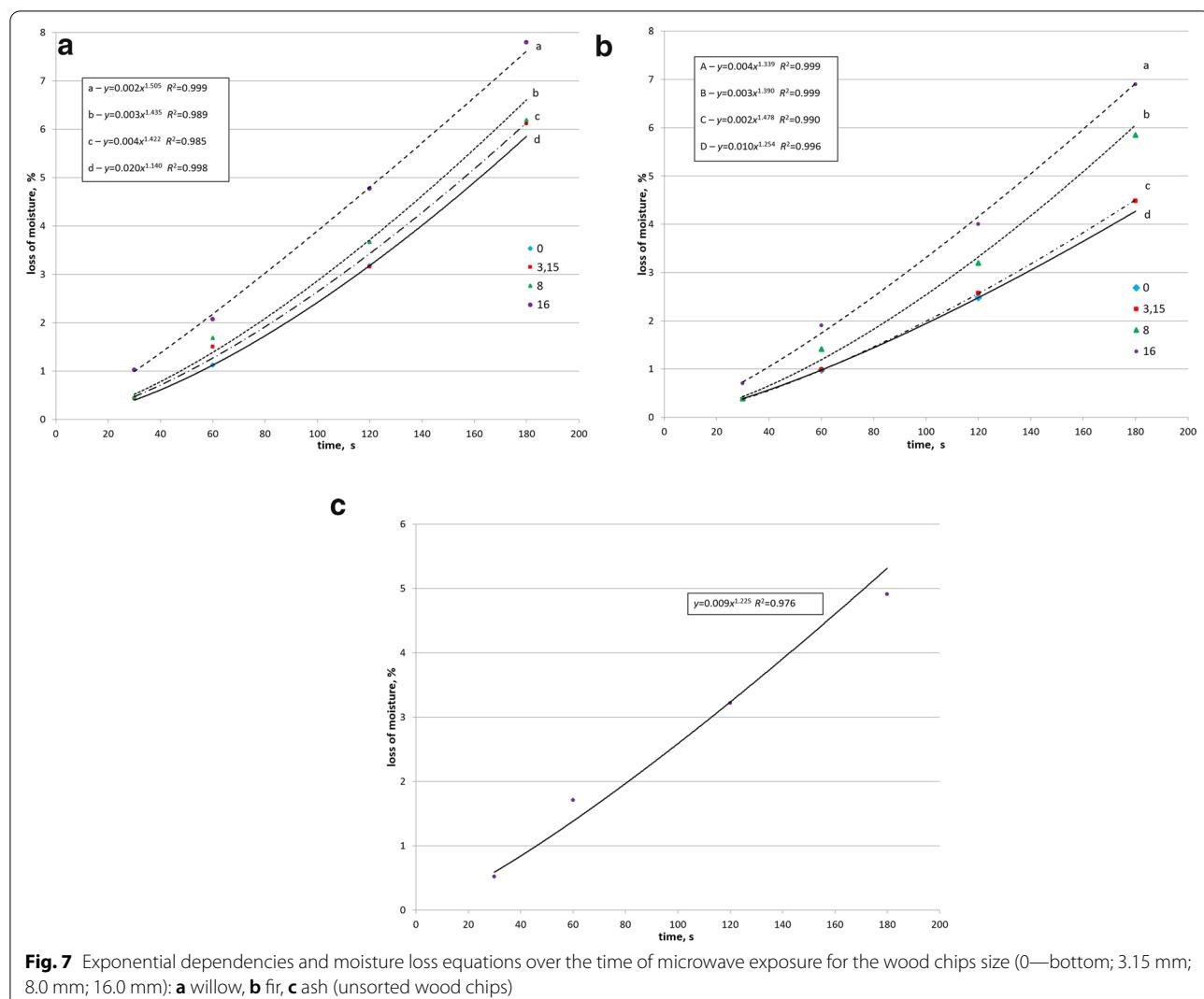
Species	Sieve size, mm	Time, s			
		30	60	120	180
Willow	0	–	3.21 (4.64)	8.57 (12.53)	–
	3.15	1.18 (1.77)	4.30 (6.04)	8.73 (12.36)	14.95 (21.12)
	8.0	1.24 (1.93)	4.42 (6.90)	9.29 (14.55)	15.84 (25.40)
	16.0	2.43 (4.40)	4.67 (8.93)	10.78 (19.33)	17.11 (30.08)
	31.5	–	–	11.26 (21.00)	–
	63	–	–	–	–
Fir	0	–	3.77 (3.84)	9.16 (9.46)	–
	3.15	1.65 (1.46)	4.39 (3.91)	10.81 (9.77)	18.23 (16.41)
	8.0	1.51 (1.56)	5.47 (5.47)	11.95 (12.10)	19.17 (19.75)
	16.0	2.80 (3.46)	5.89 (7.38)	11.62 (15.23)	19.57 (26.94)
	31.5	–	–	11.04 (17.86)	–
	63	–	–	–	–

non-linear relationships between irradiation time and loss of moisture for the various fractions [60–62]. Strong positive correlations were identified ($r>0.9$).

The drying process was more efficient for larger fraction sizes due to the fact that bigger wood chips arranged in a thin layer were more readily swept by air which removed the evaporated moisture. Thus, induced air flow would be beneficial in the case of smaller wood chip fractions.

Multiple factor ANOVA showed significant differences for the qualitative effects of microwave irradiation time and different sieve sizes with respect to loss of moisture ($F=3.911$; $p=0.006$), but no significant differences for the qualitative effects of two wood chip species and sieve size or fir and willow chip species irradiation time and sieve size.





In addition to loss of moisture as a percentage of initial wood chip weight, Table 4 also provides that value as a percentage of initial wood chip moisture content (in brackets). As can be seen after 30 s of microwave irradiation loss of moisture amounted to 4.40% and 3.46% for the 16 mm fraction of willow and fir wood chips, respectively. In turn after a 180 s of treatment loss of moisture with respect to initial moisture content was more than 30.08% for the former and 26.94% for the latter.

The longer the microwave irradiation time, the greater the loss of moisture in ash chips. The mean moisture content decreased by 0.73% after 30 s, 2.32% after 60 s, 4.40% after 120 s and almost by 7% after 180 s (Table 5). This means that loss of moisture proceeded at a rate of 0.39% per 10 s ($R=0.995$). Statistical analysis using the Duncan test showed significant differences in microwave-induced loss of moisture with respect to unfractionated ash chips.

In the aggregate treating willow chips as if they were unfractionated, it was found that their level of moisture decreased by 1.46% after 30 s, 4.42% after 60 s, 9.23% after 120 s and 15.32% after 180 s. In the case of fir chips, the corresponding values were 1.56%, 4.91%, 11.00%, and 18.68% (Table 5). A significant linear decline in moisture content was noted for both wood chip species at a rate of 0.91% per 10 s ($R=0.998$) for willow chips and 1.13% per 10 s ($R=0.997$) for fir chips.

On the other hand, initial moisture content was not found to significantly affect the magnitude of moisture loss in wood chips as a result of a short exposure to microwave irradiation. After the various irradiation times, the Duncan test revealed no statistically significant differences in this respect between ash chips with an initial moisture content of approx. 18% and willow or fir chips with an initial moisture content of more than 60%.

Table 5 Descriptive statistics for loss of moisture, % in unfractionated willow, fir and ash chips after various microwave irradiation times

Species	Time, s	Mean %	Min. %	Max. %	Range %	Variance	SD %	CV %
Willow	30	1.46	1.15	2.43	1.28	0.30	0.54	37.20
	60	4.42	3.66	4.93	1.27	0.22	0.47	10.63
	120	9.23	8.27	10.78	2.51	0.75	0.87	9.37
	180	15.32	12.92	17.50	4.58	3.83	1.96	12.78
Fir	30	1.56	1.45	1.72	0.28	0.01	0.11	7.00
	60	4.91	3.62	5.89	2.28	0.76	0.87	17.8
	120	11.00	9.16	12.2	3.04	1.35	1.17	10.58
	180	18.68	17.53	19.63	2.10	0.44	0.66	3.55
Ash	30	0.73	0.55	1.00	0.46	0.03	0.17	23.40
	60	2.32	2.10	2.60	0.50	0.04	0.20	8.60
	120	4.40	3.94	5.04	1.11	0.18	0.42	9.50
	180	6.64	5.25	7.93	2.68	1.07	1.06	15.60

SD standard deviation, CV coefficient of variation

Calculation of unit radiant flux and unit radiant energy for microwave radiation applied to wood chips

Unit radiant flux was computed from Eq. 1 for samples of the three studied species of wood chips whose initial weight was approx. 150 g. The obtained values did not differ significantly with a mean of 5.32 W g^{-1} . In turn mean unit radiant flux calculated per loss of moisture at various time points (Eq. 2) for willow, fir and ash chips was 5.36 W g^{-1} for all three species after 30 s; 5.47 W g^{-1} , 5.46 W g^{-1} , 5.43 W g^{-1} after 60 s; 5.69 W g^{-1} , 5.64 W g^{-1} , 5.53 W g^{-1} after 120 s; and 5.89 W g^{-1} , 5.87 W g^{-1} , 5.64 W g^{-1} after 180 s, respectively (Table 6).

The RIR Tukey test for the value γ_k showed no significant differences after 30 s of chips exposure to microwave irradiation. After 60 s and 120 s, a significant difference was confirmed for ash and willow chips

($p=0.036$ and $p=0.021$), and after 180 s only willow and fir chips did not differ from each other ($p=0.905$).

Mean unit radiant energy values for loss of moisture (difference between wood chip weight before and after irradiation) calculated from Eq. 3 are given in Table 7.

As can be seen, the larger the wood chip size (from 3.15 to 16.0 mm) the lower unit radiant energy. It should be borne in mind that the results obtained for the $< 3.15 \text{ mm}$ and $> 31.5 \text{ mm}$ fractions should be treated cautiously due to the small quantity of the tested material.

Discussion

In the presented study fractionated wood chips from two tree species exhibited similar size distributions with more than 80% falling between 3.15 and 16.0 mm

Table 6 Unit radiant flux for investigated willow, fir and ash wood chips after various exposure times in W g^{-1} and its descriptive statistics

Species	Time, s	Mean	Min.	Max.	Range	Variance	SD	CV
Willow	30	5.36	5.35	5.37	0.02	0.00	0.01	0.10
	60	5.47	5.44	5.50	0.05	0.00	0.02	0.32
	120	5.69	5.59	5.99	0.39	0.02	0.14	2.39
	180	5.89	5.78	5.97	0.18	0.01	0.08	1.33
Fir	30	5.36	5.35	5.38	0.03	0.00	0.01	0.20
	60	5.46	5.42	5.51	0.10	0.00	0.03	0.62
	120	5.64	5.57	5.69	0.12	0.00	0.04	0.73
	180	5.87	5.79	5.95	0.16	0.00	0.06	0.95
Ash	30	5.36	5.35	5.38	0.02	0.00	0.01	0.19
	60	5.43	5.42	5.43	0.02	0.00	0.01	0.12
	120	5.53	5.51	5.54	0.04	0.00	0.01	0.24
	180	5.64	5.58	5.69	0.11	0.00	0.05	0.83

SD standard deviation, CV coefficient of variation

Table 7 Unit radiant energy per loss of water in fractionated willow and fir wood chips after various exposure times in kJ g^{-1}

Species	Sieve size, mm	Time, s			
		30	60	120	180
Willow	0	–	–	11.68	–
	3.15	22.43	12.96	12.50	9.44
	8.0	21.30	11.90	11.30	10.62
	16.0	12.37	10.44	9.20	8.78
	31.5	–	–	11.00	–
	0	–	22.22	13.73	–
Fir	3.15	20.60	15.47	12.44	11.09
	8.0	20.81	11.67	10.62	9.84
	16.0	–	9.72	9.69	8.89
	31.5	–	–	14.75	–

which is consistent with the results reported by Spinnelli et al. [63] and Picchio et al. [64]. The studied wood chips met the requirements of the standard PN-91/D-95009 [65] and ISO/TS 17225-9 [66]. Wood chip fractionation (sorting) is important in many manufacturing processes including the manufacture of fiberboards and oriented strand boards [67].

The suitability of the chips for a specific use (also referred as a quality), apart from the distribution of their size, is determined by the moisture content. According to the standard ISO 17225-4 [68], the limit is 35% on wet basis (53.8% on dry basis) for A2 grade wood chips, that is not fulfilled, while pursuant to the Austrian standard M 7133 it should be between 5% on wet basis (5.3% on dry basis) and 65% on wet basis (185.7% on dry basis). The moisture of investigated chips meet B grade of ISO 17225-4 [68] or I2 grade of ISO/TS 17225-9 [66].

The study material satisfied the requirements of the latter standard, while the European standard was exceeded for willow and fir chips, respectively. The high moisture content was attributable to wood chip storage prior to testing as the chips were produced within 48 h after a rainy day. Thus the wood material was not dry, but the elevated moisture content did not disqualify it from being processed.

Due to different storage conditions, the moisture content of ash chips was approx. half of that of willow and fir chips. Ash chips were not fractionated, they were only evaluated in terms of moisture changes resulting from microwave irradiation.

A study by [40] showed microwave irradiation to be more efficient than convective drying leading to energy savings of up to 50%. It was reported that during microwave irradiation water evaporates most rapidly in the

early stages of the process when moisture content is high and then the drying rate gradually decreases. In turn Li et al. [69] examined the effects of preliminary microwave irradiation on the moisture diffusion coefficient and found that the wood drying rate during a subsequent convective process was not significantly improved by microwave pretreatment. The conflicting results of the above studies were one of the reasons motivating the present investigations.

In this study, the fractionation of wood chips with high moisture content led to a considerable decrease in that parameter: by 17.11% (for 16 mm—Table 4) for willow chips and 19.57% (for 16 mm—Table 4) for fir chips as compared to approx. 6.67% (Table 5) for ash chips—unfractionated (in all cases after 3 min of drying). Greater loss of moisture was recorded for larger wood chip sizes. The difference in the loss of moisture for the 3.15–8 mm fraction irradiated for 30 s and 180 s amounted to 13.77% for willow chips and 16.58% for fir chips. The corresponding values for the 8–16 mm fraction were 14.60% and 17.66% and those for the 16–31.5 mm fraction were 14.68% and 16.77% (Table 4).

Analysis of loss of moisture after the various irradiation times (Table 4) in conjunction with unit radiant energy (Table 6) indicates that process efficiency increases with irradiation time. The most pronounced decrease in the amount of energy needed to evaporate 1 g of water was observed for the 120–180 s time range. This is largely attributable to an increase in mean wood chip temperature from initially approx. 20 to 60 °C after 30 s irradiation, 80 °C after 120 s and 130 °C after 180 s. Furthermore, the surface temperature of wood chips rose to 150 °C. These results show that wood chips should be irradiated in a continuous manner (without breaks) with a gradually decreasing microwave power to prevent local wood overheating which could potentially lead to ignition.

Statistical analysis revealed that longer exposure to microwaves would have a greater effect on larger wood chip sizes vs. smaller ones. Therefore, wood chip segregation prior to microwave irradiation is recommended. This was also corroborated by the unit radiant flux and energy values obtained for the tested wood chips.

Conclusions

The study showed a greater decrease in the moisture content for the larger sizes of fractionated willow and ash wood chips upon irradiation with the same microwave power for the same time. Thus, it is recommended that wood chips be segregated (sized) prior to microwave treatment.

The initial moisture content of wood chips was not found to significantly affect loss of moisture as the drying rates

of wood chips with higher and lower moisture content exposed to microwaves were not statistically different.

The results showed that irradiation intensity increased with the time of exposure to microwaves and unit radiant energy per unit of evaporated moisture decreased with increasing wood chip size in the 3.15–31.5 mm range.

Abbreviations

ANOVA: Analysis of variance; CV: Coefficient of variation; F: F-test; max: Maximum; min: Minimum; m_k : The weight of the material after, g; m_p : The weight of the material before, g; OSB: Oriented standard board; p : Statistical significance; P : Power microwave, [W]; r : Pearson correlation coefficient; SD: Standard deviation; γ_k : Unit radiant flux, after, [$W\text{ g}^{-1}$]; γ_p : Unit radiant flux, before, [$W\text{ g}^{-1}$]; ε_u : Unit radiant energy per loss of moisture, [$J\text{ g}^{-1}$]; τ : Time microwave, s.

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Authors' contributions

MA—concept, literature review, methods, measurements, developing the results, statistical analysis, conclusions, writing; KS—literature review, methods, measurements, developing the results, ET—measurements; WZ—literature review, methods, analysis, conclusions. All authors read and approved the final manuscript.

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Availability of data and materials

All data and source materials are placed on the server of the Department of Biosystem Engineering of SGGW. Data can be sent, please send requests to the author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare the lack of competing interests.

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