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Influence of the Duration of Microwave Irradiation of Scots Pine (*Pinus sylvestris* L.) Cones on the Quality of Harvested Seeds

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Abstract: To improve the process of seed extraction, new solutions have been investigated in an attempt to develop guidelines for the construction of small seed extraction equipment. One of the solutions proposed in this field is the use of electromagnetic radiation in the first stage of hulling cones, reducing their initial moisture content, which will result in quicker scale opening. It is proposed that cones should be irradiated for a relatively short period in the first stage. This operation will allow a quicker loss of moisture from the cones that are still closed, which will result in a more intensive opening of cone scales and will also positively affect the exposure of seeds for the next phase of hulling. The aim of the study was to evaluate the effect of microwave irradiation of pine cones on the quality of the seeds obtained. Cones were exposed to microwaves produced by an 800 W generator. The research was performed in several modes, in which the variable parameters were the duration of microwave irradiation, arrangement of cones with the apex pointed towards either the inner or outer part of the turntable, and the number of cones. The temperature distribution on the surface of and inside the cones was determined using the THERM v2 (Vigo System SA, Ożarów Mazowiecki, Poland) thermal image processing software. We also assessed the energy (vitality) and germinability (quality class) of seeds that were not exposed and those after microwave treatment. The results of the research allowed us to state that, with the assumed parameters of the process, it is possible to obtain second quality class seeds after exposure to microwaves for 5 s. This result was comparable to the quality of seeds obtained without the use of microwaves. When the irradiation time was increased above 5 s, the vitality of seeds decreased and their quality was not satisfactory.

Keywords: scots pine; cone; seeds; electromagnetic radiation; seed quality class; thermal imagery

1. Introduction

Significant progress has been made in recent years in the field of seed science, which has contributed to the modernisation of existing technical infrastructure facilities or construction of new facilities used for seed collection, quality assessment, and storage. Due to the high processing capacity that these facilities require, the need for regular deliveries of large amounts of cones is high in order to reduce extraction costs. However, this is often not easy to achieve as the availability of cone crops depends on seed years [1]. The most widespread forest tree in Central and Eastern Europe is Scots pine (*Pinus sylvestris* L.), hence the seed material of this species is typically used for studies.

In the past, various attempts were made to minimise the time of seed extraction. These included raising the temperature of extraction [2], lowering pressure in a drying chamber, mechanical cone trimming (e.g., by cutting off the base), sorting cones by size, or soaking cones in water during the stepwise extraction process [3]. Although numerous studies were conducted, no positive effects in terms of significant reduction in extraction time emerged. One of the reasons for this was the high sensitivity of seeds during drying to external factors, such as excessive temperature or inappropriate air humidity [1].

The observation of the cone hulling process and the review of the existing literature on the subject [2,4,5] resulted in the identification of a problem obtaining coniferous tree seeds in a manner that ensures their optimum quality.

The heat and mass transfer in biological materials subjected to electromagnetic radiation (EMR) has been well documented. Consequently, microwave drying is widely considered one of the best methods for the intensification of these processes [6–8]. However, there are divergent opinions on the influence of EMR on biological materials, as it depends on numerous factors, including the moisture content, structure and composition of the material, as well as the frequency and length of the electromagnetic waves used [9–11]. It has been well documented that prolonged microwave irradiation of biological samples can cause structural damage to both tissues and cells [12–23]. The available studies have also investigated the effect of intermittent microwave drying on biophysical properties of various plants, such as rice [24], colza [25], or tree seeds and seedlings [26].

In the case of seeds, a rapid rise in temperature under the influence of microwaves results in the reduction or loss of their viability. The effects of microwave irradiation on Scots pine cones were discussed by Aniszewska and Słowiński [27], who determined the maximum exposure time for enabling the extraction of good quality seeds. Aniszewska also investigated an increase in the surface temperature of cones, depending on the microwave irradiation power and duration [1]. Microwave-assisted drying of canola, soybean, and corn was carried out by Hemis et al. [28], who concluded that microwaves could lead to cracks in seeds, reducing their quality. Based on the aforementioned studies, it cannot be categorically stated whether short-time exposure of biological materials, particularly cones, to radiation is harmful or not.

Furthermore, new solutions have been recently investigated to improve the seed extraction process. Attempts have been made to draw guidelines for the construction of small extraction devices, which could increase the efficiency of seed collection. Such devices could be used to dry small quantities of cones using enhanced extraction technologies. One solution, closely related to this, is the use of microwaves in the initial phase of the one- or two-stage process of seed extraction from cones in order to reduce their initial moisture content. The decrease in cone moisture reduces the time taken for scales to lean from the axis. It is proposed that cones should be irradiated for a relatively short period in the first stage of the extraction process, which would result in the rapid loss of moisture from the still-closed cones. This would lead to weight loss and initiate the opening of scales, that is, their separation from one another. Such treatment improves the leaning of scales and exposure of seeds in the next phase of the first stage of cone hulling, which is conducted in an extraction chamber or kiln [1]. However, a precondition for the widespread use of microwaves is the investigation of their effects on seed viability. Hence, the ultimate power and duration of microwave irradiation needs to be carefully examined.

Our study on potential extraction process improvements aimed to evaluate the effect of the duration of exposure to microwave radiation and cone temperature on the quality of Scots pine (*Pinus sylvestris* L.) seeds, collected in 2015 and held in cold storage for three years. For this purpose, the physical parameters of cones, such as weight, length, and thickness, were examined. Furthermore, (a) cone exposure to fixed power microwaves in a number of modes, differing in the duration of irradiation and the number of cones; (b) determination of the temperature distribution on the surface of and inside the cones; and (c) assessment of the quality of seeds, based on their germinability, were measured to highlight the effect of the duration of microwave radiation on the quality of harvested seeds.

2. Materials and Methods

2.1. Study Material and Physical Characteristics of Cones

The material for the study was obtained from the Brzesko Forest District, State Forest Regional Directorate in Cracow. It was collected from a pine stand aged 119 years (from an identified source: region of origin: 6th natural forest region, commercial forest growing in a fresh mixed deciduous forest site (49°58′ N, 20°33′ E). The cones were harvested in December 2015 and subsequently cold stored in controlled ambient conditions: temperature of 5 °C and relative humidity of 18% with a maximum deviation of ± 2%.

A total of 225 cones, randomly selected from a wider batch, were investigated. The length, thickness (the largest diameter), and the distance between the maximum thickness point and the cone base were measured using an MIB digital calliper (MESSZEUGE, Spangenberg, Germany) with an accuracy of 0.01 mm [29]. The initial weight and the final weight after drying were determined using a WPS 210S moisture balance (RADWAG, Radom, Poland) with an accuracy of 0.001 g.

2.2. Microwave Irradiation and Temperature Distribution

An R200WE laboratory microwave generator (SHARP, Osaka, Japan), with a maximum output power of 800 W and supplied with an alternating current of frequency of 50 Hz and voltage of 230 V, was used in the study. The samples were placed under the generator, at a distance of 160 mm, on a glass turntable with a diameter of 255 mm.

The temperature distribution was determined using pictures taken with a VIGOcam v50 thermal imaging camera (Vigo System S.A., Ożarów Mazowiecki, Poland) with an IR (Infrared) resolution of 384 × 288 px and thermal sensitivity < 70 mK. The temperature reading range was −20 to +120 °C. The objects whose temperatures were to be measured were placed on a black mat base at a distance of 500 mm from the lenses. The camera settings included measurement parameters (target distance: 500 mm, ambient temperature: 22 °C, ambient humidity: 48%) and emissivity in the 8–14 μm band for the surface temperature of 0 °C, corresponding to the investigated material (wood): 0.95. The THERM v.2.29.3 software (Vigo System S.A., Ożarów Mazowiecki, Poland) was used for thermal image processing.

Thermal captions of the samples, before microwave irradiation (reference samples) and following irradiation (upon completion of cone heating), were taken using a thermal imaging camera.

In order to determine the temperature distribution on the external surface, hot cones were photographed in whole (Figure 1a). Next, to determine the temperature inside, cones were cut with an Ulu knife along the axis (Figure 1b) and photographed again with a thermal imaging camera. The cutting knife was mounted in a screw press holder, while the material being cut was placed on a profiled base.

(**a**) (**b**) (**c**)

Figure 1. Scots pine cone: (**a**) in whole; (**b**) cut; (**c**) cut with marked halves.

Finally, to identify the cross-section spot with the highest temperature, two surfaces were marked: one on the apex side and the other on the base side of the cone (Figure 1c).

The duration of the entire study procedure, from turning on the microwave generator to taking pictures with a thermal imaging camera, was very short, just 15–30 s, depending on the measurement mode.

Following microwave irradiation, cones were stored for 21 days until spontaneous opening, when seeds could be collected.

2.3. Measurement Modes

Three primary measurement modes (W1, W2, and W3) were applied for various combinations of cone arrangement and irradiation time, resulting in a total of 15 combinations (Table 1).

Table 1. Measurement modes.

Mode	Variant	Cone Arrangement	Number of Cones Under the Generator (pcs.)	Duration of Microwave Irradiation (s)
W1	-	-	1	5, 7, 10
W2	W2a	Apexes towards the centre	3	5, 10, 15
	W2b	Apexes towards the edge	3	5, 10, 15
W3	W3a	Apexes towards the centre	5	5, 10, 15
	W3b	Apexes towards the edge	5	5, 10, 15

In mode 1 (W1), a single cone was placed at the centre of the turntable (Figure 2a). In mode 2 (W2), three cones were placed on the turntable with apexes pointing either towards the centre (W2a, Figure 2a) or towards the edge (W2b). In mode 3 (W3), five cones were placed on the turntable with apexes pointing either centrewise (W3a) or outwards (W3b, Figure 2c).

(**a**) (**b**) (**c**)

Figure 2. Cone arrangement on the turntable: (**a**) single cone (W1); (**b**) three cones with apexes pointing towards the centre (W2a); (**c**) five cones with apexes pointing towards the edge (W3b).

Three different times of cone exposure to microwave irradiation were applied in each mode. However, in mode W1, a sample self-ignited after 15-second exposure to microwaves. Therefore, a different time sequence was applied in this mode, which resulted in a reduction of the maximum duration of irradiation to 10 s.

The experimental procedure was repeated 25 times. Consequently, measurements were completed for 25 cones in mode W1, 75 cones in mode W2, and 125 cones in mode W3.

2.4. Seed Quality

After cone opening, seeds were manually extracted and dewinged. Then, the quality of seeds was assessed by determining their germination energy and capacity in accordance with the standards [4]

PN-76/9211-02 [30] and PN-R-65700 [31]. A Jacobsen germinator (LABORSET, Łódź, Poland), featuring an electronic lighting and water temperature control system, was used for this purpose [32].

2.5. Statistical Analysis

Statistical analysis of the physical characteristics of the studied cones was performed using Statistica 13 software (Dell Inc., Round Rock, USA). The distribution of each parameter was tested for normality using the Shapiro–Wilk test. The differences in mean values of the parameters were determined using ANOVA coupled with Tukey's HSD (honest significant difference test) post hoc test for unequal sample sizes. The analysis was performed at the significance level $\alpha = 0.05$.

3. Results

3.1. Physical Characteristics of Scots Pine Cones

Statistics of the physical parameters of the cones used in the study are presented in Table 2. The physical characteristics of the study material were found to be within the typical range for Europe, where the length of Scots pine cones ranges from 19 to 70 mm, their thickness ranges from 12 to 35 mm [33,34], and their weight ranges from 5 to 18.4 g [1,35]. The mean moisture content was 34%. The individual parameters had a normal distribution, which was confirmed with the Shapiro–Wilk test.

Table 2. Statistics of the physical parameters of the Scots pine cones used in the study.

Statistics	Length (mm)	Thickness (mm)	Distance Between the Maximum Thickness Point and the Cone Base (mm)	Initial Weight (g)
Mean (±SD)	43.92 ± 4.2	19.87 ± 1.64	11.12 ± 1.6	6.789 ± 1.68
Minimum	35.2	16.2	7.0	4.224
Maximum	57.6	25.7	18.7	12.973
Range	22.4	9.5	11.7	8.749
Coefficient of variation	9.50	8.26	13.9	24.7
Standard deviation	0.28	0.11	0.10	0.11

The analysis demonstrated a positive correlation between the thickness (D, mm) and length (H, mm) of cones in the study batch. This was described with linear Equation (1), where the correlation coefficient exceeded the critical value r = 0.1430 (the latter generally depends on the sample size and equation degree) [36]. The equation indicates that an increase of 1 mm in cone length corresponds to an increase of around 0.23 mm in cone thickness:

$$D = 0.2348H + 0.95586;\ \mathrm{r} = 0.5983. \quad (1)$$

In the first and second primary measurement modes (W1 and W2), the initial weight of the cones did not differ in a statistically significant way for various times of exposure to microwave irradiation ($p > 0.21$). In the third mode (W3), no significant differences in weight were found between the samples exposed for 5 and 10 s, whereas the weight of the cones exposed for 15 s was the smallest and differed statistically ($p < 0.01$) from the weight of the cones for other exposure times; the difference in the average weight between these batches was 0.2–0.5 g.

3.2. Loss of Weight under the Influence of Microwaves

The loss of weight in the studied cones as a result of microwave irradiation in the primary measurement modes, without accounting for cone arrangement, is shown in Table 3.

Table 3. Loss of weight in the primary measurement modes (mean ± SD).

	Loss of Weight (g)			
Exposure Time	**5 s**	**7 s**	**10 s**	**15 s**
W1	0.014 ± 0.008	0.021 ± 0.018	0.103 ± 0.049	-
W2	0.006 ± 0.003	-	0.037 ± 0.018	0.097 ± 0.037
W3	0.005 ± 0.003	-	0.022 ± 0.007	0.054 ± 0.022

In the mode W1, the loss of weight following microwave irradiation averaged 0.014 g (or 0.15% of the initial weight) after 5 s, 0.021 g (or 0.27%) after 7 s, and 0.103 g (or 1.10%) after 10 s. The linear dependence between loss of weight in the cones and time of exposure to microwaves was described with Equation (2) and is shown in Figure 3.

$$y_{W1} = 0.0183x - 0.0849;\ \mathrm{r} = 0.7732. \tag{2}$$

where y_{Wi} is a loss of weight (g), w_i is a model/variant (Table 1), x is time of exposure to microwaves (s).

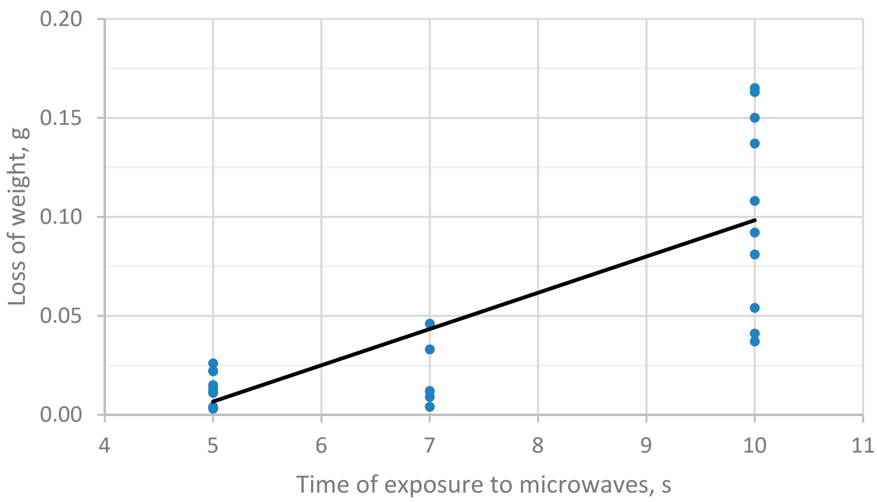

Figure 3. Dependence between loss of weight and time of exposure to microwaves in the first measurement mode (W1).

The trend line indicates that an increase in the time of cone heating from 5 to 10 s increased the loss of weight by 0.089 g.

Statistical analysis showed no significant difference in the loss of weight in cones between exposure times of 5 and 7 s ($p = 0.95$), and these data can be considered as a uniform group. However, a higher loss of weight was observed for the 10-second exposure and was statistically significantly different from the results obtained for other exposure periods ($p < 0.01$).

The loss of weight in the cones in the second mode (W2), that is, the simultaneous heating of three cones placed on the turntable for 5, 10, or 15 s, is presented in Table 3. Loss of weight averaged 0.006 g (or 0.07% of the initial weight) after 5 s of heating, 0.037 g (or 0.50%) after 10 seconds, and 0.097 g (or 1.34%) after 15 s.

The relationship between loss of weight and time of exposure in Scots pine cones to microwaves is shown in Figure 4. For mode W2, it was described with Equation (3), without differentiating between the cone arrangements submodes (y_{W2}).

$$y_{W2} = 0.0087x - 0.0417;\ \mathrm{r} = 0.8414. \tag{3}$$

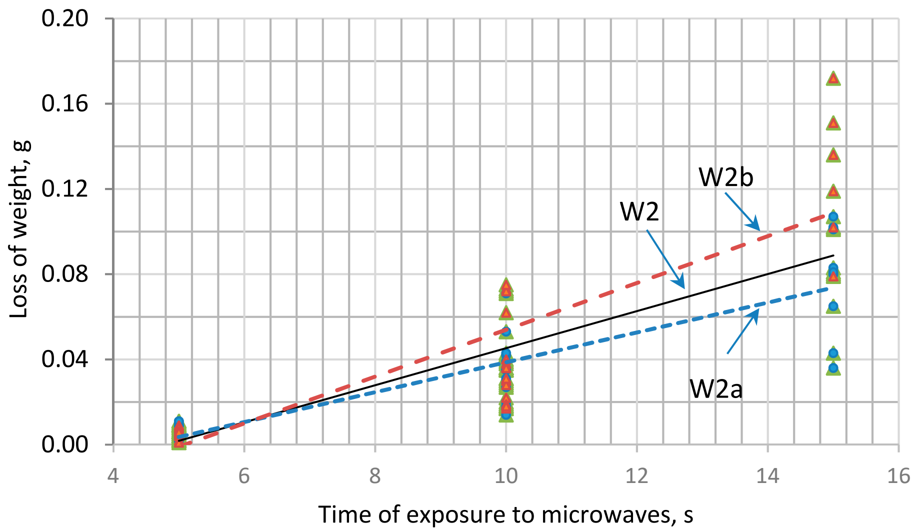

Figure 4. Dependence between loss of weight and time of exposure to microwaves in the second measurement mode (W2, W2a, W2b).

It can be seen that the longer heating of cones contributed to increased loss of mass in a similar way to single cones exposed to irradiation in the mode W1.

In the mode W2, ANOVA coupled with a post hoc test indicated a significant effect of the time of exposure of a cone to microwaves on its loss of weight ($p < 0.01$). The greater the time of exposure, the higher the weight loss of the cones.

Finally, the loss of weight in the third study mode (W3), that is, five cones placed on the turntable and exposed to microwaves for 5, 10, or 15 s, is presented in Table 3 and Figure 5. Loss of weight averaged 0.005 g (0.08% of initial weight) after heating for 5 s. Upon exposure to microwaves for 10 and 15 s, loss of weight increased to 0.022 g (0.36% of initial weight) and 0.054 g (1.05% of initial weight), respectively.

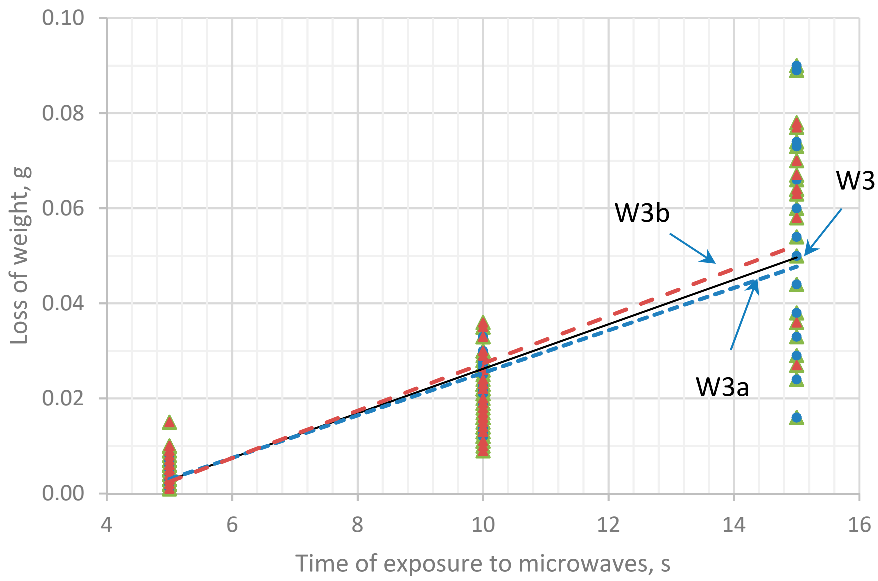

Figure 5. Dependence between loss of weight and time of exposure to microwaves in the third measurement mode (W3, W3a, W3b).

The change in weight in the cones in mode W3 was described with Equation (4), which aggregates both cone arrangement submodes:

$$y_{W3} = 0.0047x - 0.0206;\ \mathrm{r} = 0.8361. \tag{4}$$

Similar to the W2 mode, a statistically significant difference occurred between the mean loss of weight in cones for various exposure times ($p < 0.01$). Loss of weight increased along with an increase in the time of exposure to microwaves.

Loss of weight, accounting for the cone arrangement on the turntable under a microwave generator, is presented in Table 4. The loss of weight in the pine cones, depending on the time of their exposure and their arrangement under a microwave generator in submodes W2a and W2b, is shown in Figure 4. The trend line for the cone arrangement W2b is higher than the trend line for the arrangement W2a, which indicates a higher loss of weight for cones with apexes pointing towards the turntable edge. ANOVA showed a relationship between loss of weight and the cone apex arrangement centrewise or outwards ($p < 0.01$). A post hoc test further demonstrated that cone arrangement did not affect loss of weight for exposure times of 5 s ($p = 0.90$) or 10 s ($p = 0.39$), while it did affect the loss of weight ($p = 0.01$) in the case of 15-second exposure.

Table 4. Loss of weight (g) following irradiation, by cone arrangement, in the second (W2a and W2b) and third (W3a and W3b) study modes.

	Loss of Weight (g)		
Exposure Time	**5 s**	**10 s**	**15 s**
W2a	0.006 ± 0.003	0.034 ± 0.015	0.078 ± 0.025
W2b	0.006 ± 0.002	0.040 ± 0.021	0.127 ± 0.034
W3a	0.005 ± 0.002	0.022 ± 0.006	0.050 ± 0.025
W3b	0.006 ± 0.003	0.021 ± 0.008	0.060 ± 0.017

Loss of weight, depending on the duration of microwave irradiation for the cone arrangement submodes W2a (y_{W2a}) and W2b (y_{W2b}), was described with linear Equations (5) and (6), respectively:

$$y_{W2a} = 0.0011x - 0.0559;\ \mathrm{r} = 0.8749, \tag{5}$$

$$y_{W2b} = 0.0007x - 0.0314;\ \mathrm{r} = 0.8714. \tag{6}$$

A similar dependence of the loss of weight in cones was observed in the submodes W3a and W3b (Figure 5). As in the second study mode, a slightly higher weight loss, in both absolute and relative terms, occurred in cones with apexes pointing outwards. Cones with apexes pointing towards the turntable centre lost slightly less moisture. ANOVA coupled with a post hoc test demonstrated that the duration of microwave irradiation resulted in a significant loss of weight ($p < 0.01$) for both cone arrangements (W3a and W3b), whereas cone arrangement had no effect on the loss of weight for individual exposure times ($p > 0.17$).

Loss of weight, depending on the duration of microwave irradiation for the cone arrangement submodes W3a (y_{W3a}) and W3b (y_{W3b}), was described with the linear Equations (7) and (8), respectively:

$$y_{W3a} = 0.0050x - 0.0224;\ \mathrm{r} = 0.8434, \tag{7}$$

$$y_{W3b} = 0.0045x - 0.0193;\ \mathrm{r} = 0.8117. \tag{8}$$

The correlation between increased loss of weight and higher time of exposure to microwaves, which was revealed in all cases, confirms the results obtained by Çelen [17], who carried out a similar study on persimmon drying (through also changing the microwave power).

3.3. Change in Cone Temperature under the Influence of Microwaves

The maximum temperatures of Scots pine cones, both intact (whole cones) and cut, with the indication of the relevant portion of the cone as recorded by a thermal imaging camera, are presented in Table 5.

Table 5. Maximum temperatures of intact and cut cones by measurement modes.

Time of Exposure to Microwaves (s)	Maximum Temperature of the Whole Cone (°C)	Half No.	Maximum Temperature of the Cone Half (°C)
W1			
5	62.52 ± 10.24	1	53.25 ± 15.24
		2	43.10 ± 7.04
7	88.29 ± 14.49	1	60.58 ± 14.37
		2	72.74
10	103.43 ± 13.22	1	75.58 ± 4.69
		2	77.67
W2a			
5	63.07 ± 11.76	1	49.15 ± 6.36
		2	48.04
10	84.69 ± 8.59	1	68.35 ± 8.93
		2	63.71 ± 9.03
15	99.23 ± 0.16	1	-
		2	78.76 ± 0.45
W2b			
5	48.58 ± 7.78	1	42.43 ± 5.01
		2	-
10	79.35 ± 10.87	1	66.5 ± 4.48
		2	56.65 ± 0.99
15	95.19 ± 1.45	1	75.85 ± 1.42
		2	-
W3a			
5	52.53 ± 6.29	1	43.73 ± 4.42
		2	50.00
10	78.35 ± 9.15	1	60.58 ± 1.55
		2	-
15	85.14 ± 3.59	1	66.56 ± 3.63
		2	67.21
W3b			
5	42.65 ± 7.04	1	37.70 ± 4.23
		2	-
10	70.26 ± 6.02	1	60.47 ± 1.81
		2	60.19
15	84.26 ± 3.75	1	66.17 ± 4.21
		2	-

In the study mode W1 (Table 5), statistical analysis indicated that the maximum temperatures of whole cones did not differ in a statistically significant way between the microwave exposure times of 7 and 10 s ($p = 0.16$). However, in the experimental protocol of 5-second exposure, the maximum temperature was the lowest, and differed significantly from the maximum temperatures after exposure for 7 ($p = 0.01$) or 10 s ($p < 0.01$).

In mode W2, without accounting for cone arrangement submodes, statistical analysis demonstrated that the maximum temperatures of whole cones did not differ in a statistically significant way between microwave exposure times of 10 and 15 s ($p = 0.08$). However, in the case of 5-second exposure, the maximum temperature was the lowest and differed significantly from the maximum temperatures after exposure for 10 ($p < 0.01$) or 15 s ($p < 0.01$).

As far as the cone arrangement with apexes pointing towards the turntable centre is concerned (W2a, Table 5), there was no statistically significant difference in the maximum temperature between microwave exposure times of 10 and 15 s ($p = 0.09$), while such differences occurred for other pairs of exposure times ($p < 0.01$). In the W2b submode, significant differences in the maximum temperature were observed between all exposure times ($p < 0.02$).

Furthermore, for exposure times of 5 and 10 s, there were no significant differences in temperatures depending on the arrangement of cones on the turntable under a microwave generator ($p > 0.42$), while, for 15-second exposure, cone arrangement had a significant effect on the maximum temperature of cones ($p = 0.03$).

In mode W3, without accounting for cone arrangement submodes, ANOVA coupled with a post hoc test indicated that the maximum temperatures of whole cones did not differ in a statistically significant way between microwave exposure times of 10 and 15 s ($p = 0.06$), while, in the cases of 5-second exposure, the maximum temperature was the lowest and differed significantly from the maximum temperatures after exposure for 10 ($p < 0.01$) or 15 s ($p < 0.01$).

Analysing the data for the arrangement of cones with apexes pointing towards the turntable centre (W3a), there was no statistically significant difference in the maximum temperature between microwave exposure times of 10 and 15 s ($p = 0.11$), while such differences occurred for other pairs of exposure times ($p < 0.01$). A similar tendency was observed for the W3b submode, in which cones were arranged with apexes pointing towards the edge. Mean cone temperatures following exposure for 10 or 15 s can be considered as a uniform data set ($p = 0.15$), whereas differences in mean values occurred for other pairs of exposure times ($p < 0.01$).

Statistical analysis confirmed the positive correlation between the temperature of cones and their arrangement with apexes pointing either outward or centrewise for the 5-second exposure time ($p = 0.03$), while, in the case of microwave exposure of 10 or 15 s, cone arrangement had no significant effect on temperature ($p > 0.84$).

The presented thermal images of the studied materials (Figure 6) indicate non-uniform temperature distribution for both the whole cone (Figure 6a,c) and the cone cut in half with a guillotine cutter (Figure 6b,d) in the mode W1. As far as the arrangement of the study objects is concerned, warmer colours were seen at the cone base, which implies that the temperature of the base was higher compared to that of the apex.

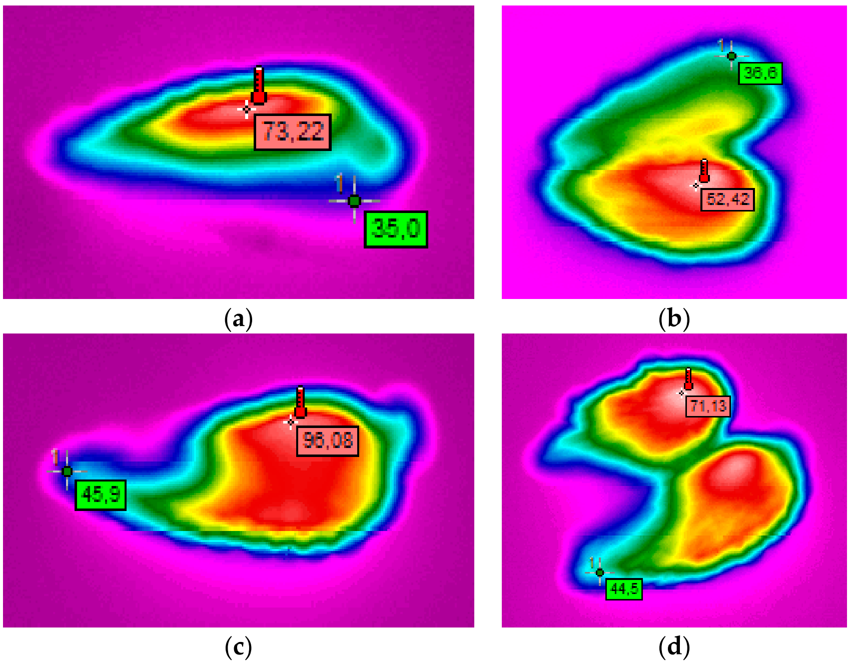

Figure 6. Thermal images of cone heating in the study mode W1: (**a**) whole cone, 7 s; (**b**) cone halves, 7 s; (**c**) whole cone, 10 s; and (**d**) cone halves, 10 s.

In mode W2, upon microwave irradiation for 5 s, the maximum temperature of whole cones and their halves was higher for the cone arrangement with apexes pointing centrewise (W2a). When cones were exposed to microwaves for 10 or 15 s, the maximum temperatures were comparable, regardless of the cone orientation with respect to the turntable. For 15-second exposure, the temperature approached 100 °C for whole cones and 80 °C for cone halves. These figures are comparable to those obtained by Çelen [17] during the microwave drying of vegetables (87–155 °C). Sample images of both intact and cut cones, made with a thermal imaging camera, are shown in Figure 7.

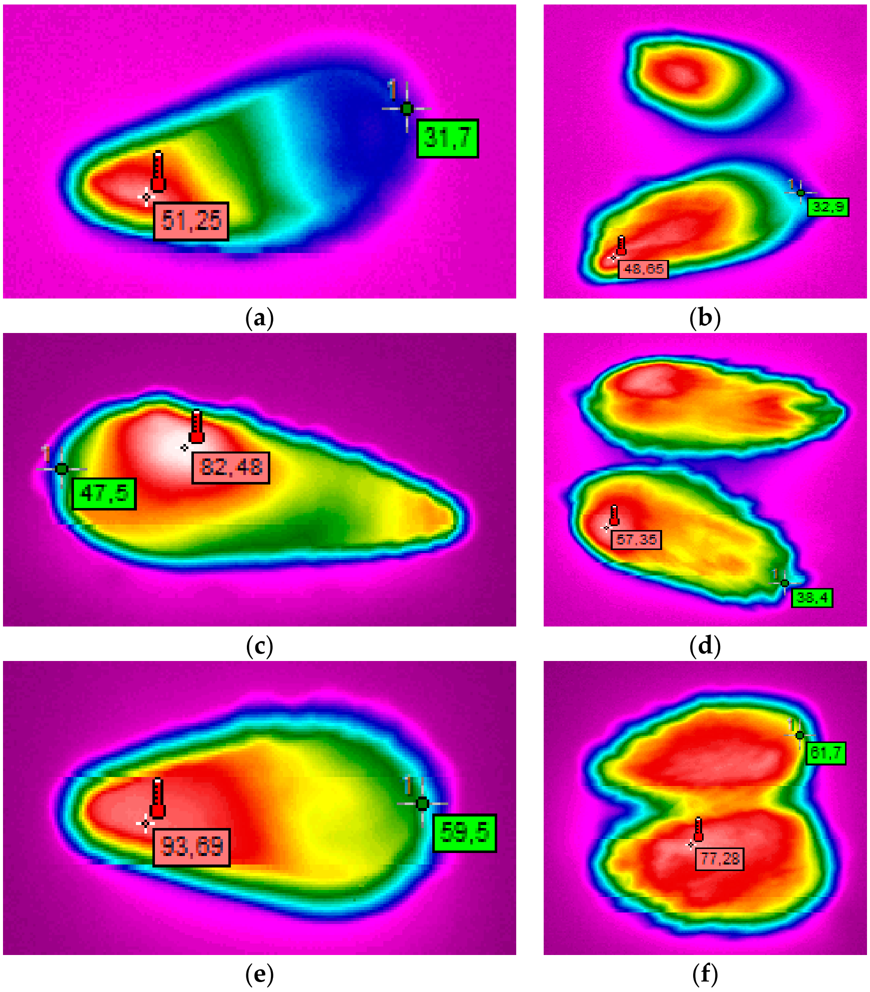

Figure 7. Thermal images of cone heating: (**a**) whole cone with the apex pointing outwards, heated for 5 s; (**b**) cone halves with the apex pointing outwards, heated for 5 s; (**c**) whole cone with the apex pointing centrewise, heated for 10 s; (**d**) cone halves with the apex pointing centrewise, heated for 10 s; (**e**) whole cone with the apex pointing outwards, heated for 15 s; and (**f**) cone halves with the apex pointing outwards, heated for 15 s.

Based on the obtained results, it was concluded that the arrangement of cones under a microwave generator with apexes pointing towards the centre of the turntable results in a faster heating of the cone bases, while the opposite arrangement results in faster heating of the cone apexes.

In mode W3, in the case of 5-second exposure, temperatures of both whole cones and cone halves were significantly higher for the cone arrangement with apexes pointing centrewise (W3a), whereas, in the case of microwave irradiation for 10 or 15 s, no significant differences in cone temperatures were observed for both arrangements (W3a, W3b). In the majority of cases, the highest temperature occurred in the apex portion of both whole cones and cones cut in half.

Considering the number and distribution of seeds in cones [37], it is more favourable for seed viability to place a greater number of cones under a microwave generator with apexes pointing towards the edge of the turntable, as there are less seeds at the apex than in the middle or at the base of cones.

3.4. Analysis of the Germination Energy and Capacity of Scots Pine Seeds

The results concerning the germination energy and capacity as well as quality of seeds for the three primary study modes are presented in Table 6.

Table 6. Quality class of Scots pine seeds for the three measurement modes.

Mode	Microwave Exposure Time (s)	Germination Energy (%)	Germination Capacity (%)	Seed Quality Class
W1				
	5	38	42	substandard
	7	33	35	substandard
	10	10	11	substandard
W2				
	5	62	65	substandard
	10	19	20	substandard
	15	0	0	substandard
W3				
	5	74	81	II
	10	39	45	substandard
	15	2	3	substandard

In modes W1 and W2, seeds exposed to microwave irradiation fell short of the lowest quality class as their germination energy was below the threshold of 50% and their germination capacity was below 70% for all three exposure times. Only the seeds irradiated for 5 s in the study mode W3 reached quality class II. Their germination energy was 74% and their germination capacity was 81%, thus falling within the range of 70% to 84% for germination energy and 81% to 90% for the germination capacity specified in the relevant standard. Increasing the duration of microwave irradiation to 10 or 15 s led to the reduced viability of seeds, which were classified as substandard.

In the control sample (not exposed to microwave radiation), seeds reached a germination energy of 72% and germination capacity of 83%, so they could be classified as quality class II.

For microwave exposure times of 5 and 10 s, in all study cases, there was a clear relationship between seed viability (germination energy and capacity) and the number (total weight) of cones placed together under a microwave generator. An increase in the number of cones placed under a microwave generator resulted in a higher germination energy and capacity of seeds.

4. Discussion

The data presented here indicate that exposure to microwaves for more than 5 s caused seed damage. In seed extraction plants, pine cone hulling temperatures do not exceed 50 °C [2,5,38]. Subsequently, extracted seeds, depending on the species, are dried at temperatures of up to 45 °C, as a higher temperature results in reduced seed viability or even damage.

In the current study on microwave irradiation, the highest temperatures were reached in cones placed individually under a microwave generator, while temperatures were lower when three or five cones were placed together on the turntable. Following 5-second exposure to microwaves, temperatures recorded on the cone surface exceeded 60 °C, implying that the temperatures inside the cone were over 40 °C. In the case of 15-second exposure, a temperature close to 100 °C was recorded on the cone surface, which corresponded to approximately 80 °C inside. The temperatures observed upon short exposure times were close to the surface temperatures of coffee beans (approx. 67–72 °C) reached by Dong et al. [39] by using a microwave power of 0.5–1.0 kW.

The moisture content levels to which seeds can be safely dried are significantly influenced not only by ambient temperature but also by air humidity [40], which should not exceed 28% on average. According to studies by Załęski and Aniśko [5] and Aniśko et al. [41], the viability of seeds in drying is reduced not only by high temperatures, but also by intensive tissue dehydration. Furthermore, the seeds of various tree species react differently to drying [8,40]. The minimum admissible moisture content for Scots pine seeds is 3.5%, and the same applies to black alder and common birch; the maximum drying temperature for Scots pine, as well as black alder and common birch seeds, is 45 °C [5].

Although the use of microwaves in drying biological materials has been the subject of numerous studies in recent years [42,43], the problem of uneven heating remains a barrier to industrial application. Hence, it is obvious that devices using EMR should be adapted to the drying process instead of adapting the process and materials to standard microwave systems. In order to mitigate the adverse effects of high temperatures, the optimum model for microwave power control during drying needs to be developed. Microwave power should be gradually reduced depending on the weight and number of cones in hulling, which, combined with the monitoring of the moisture content of the material, should result in the extraction of seeds with the desired properties after a relatively short time of drying. The relationship between seed quality and microwave power and between the weight of the material and exposure time need to be investigated by determining radiation flux (W/g) and unit irradiation (J/g).

5. Conclusions

Loss of weight increased along with the time of the cones' exposure to microwaves. Depending on the study mode, weight loss ranged from 0.005 g (W3) to 0.103 g (W1). Loss of weight was also related to the number of cones placed under a microwave generator. The greater the number of cones, the lower the weight loss and the higher the quality of the extracted seeds.

Analysis of the maximum temperature of Scots pine cones, both intact and cut, revealed that the portions further away from the turntable centre became hotter. Furthermore, cone bases reached higher temperatures with cone apexes pointing centrewise, rather than outwards.

Taking into consideration all the experimental conditions, cone exposure to microwaves for more than 5 s significantly reduced the viability of seeds. For 15-second microwave irradiation, a rise in temperature resulted in damage to seeds and loss of germinability. The seeds extracted from Scots pine cones irradiated for 5 s in the mode W3 reached the quality class II, which was the highest among all studied cone batches and the same as that of their control counterparts.

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