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Article

Sonification of Potato Tubers as an Innovative Method for Improving the Quality of Potato Chips

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Abstract

Modern agriculture aims to reduce the use of pesticides in favor of methods that provide high-quality raw materials for the agri-food industry. The aim of the study was to determine the effects of using ultrasound in an aquatic environment on potato tubers as a pre-planting treatment. A three-year field experiment was conducted in central-eastern Poland using the randomized sub-block method in a dependent design, split-plot, in three replications. The primary factor was the cultivation technology: (a) with ultrasonic treatment of seed potatoes before planting and (b) traditional, without ultrasonic treatment. The second-order factor was eight edible potato varieties of different earliness classes. After harvest, the effect of this method on the quality parameters of the raw material and potato chips obtained from it was assessed. Sonification helped improve the processing quality of potato tubers. Chips obtained from tubers subjected to sonication were characterized by a lighter color, better visual and organoleptic evaluation, as well as less discoloration of this product and fewer wet spots, compared to chips obtained from tubers grown traditionally. The results of the study indicate that ultrasonic treatment of seed potatoes can be an effective method of improving the quality of raw material for processing. Further research should focus on the optimization of sonication parameters and the economic analysis of its implementation on an industrial scale. The study you provided found promising results, showing that sonication improved the processing quality of potato tubers, leading to lighter, visually appealing, and tastier chips with fewer defects compared to traditionally grown potatoes.

Keywords: potato chips quality; ultrasonic pretreatment; reducing sugars; correlation analysis; moisture content; frying optimization; food processing technology; quality control

1. Introduction

Modern agriculture, facing the challenge of limiting the use of pesticides, is looking for innovative technologies to improve the quality of food raw materials. One of the promising methods is ultrasound (above 20 kHz)—a versatile technology used in medicine, industry and agrotechnics [1–5]. Their advantage is non-invasiveness, minimal impact on the environment and the ability to stimulate plant physiological processes [1,6–10]. In food processing, ultrasound is divided into:

- Low intensity (>100 kHz, <1 W/cm²)—used for non-invasive analysis of chemical composition [10].
- High intensity (18-100 kHz, >1 W/cm²)—used for tissue modification, emulsification and cleaning [10].

The mechanism of action is based on the phenomenon of acoustic cavitation, generating locally extreme conditions (up to 5000 K and 100 MPa), which can affect heat/mass exchange (stable

cavitation) or cause destructive implosions (transient cavitation) [1,10]. In the case of potato processing, the key challenge is to control the content of reducing sugars, which at high temperatures lead to undesirable browning of chips [6,11]. Their accumulation is influenced by genetic factors, abiotic stress and storage conditions [12–15]. A novel approach involves the use of sonication of tubers before planting as a method modulating plant metabolism, including the expression of genes related to sugar synthesis [11–14]. In the food industry, this technology is already used to improve the quality of products thanks to cavitation effects [3]. Modern agriculture is looking for alternative methods to reduce the use of pesticides, while ensuring high quality raw materials for the food industry. One of the promising technologies is ultrasound—acoustic waves with a frequency above 20 kHz, which are used in medicine, industry, and recently also in agrotechnics [1–5]. Their advantage is non-invasiveness, lack of negative impact on the environment and the possibility of stimulating physiological processes of plants [1,6–10]. Modern food processing technologies are also looking for solutions combining high product quality with the principles of sustainable development. In this context, ultrasound technology is gaining particular importance, which is increasingly used in various stages of food production—from pre-treatment of raw materials—to preservation processes [3,16,17]. Ultrasound (above 20 kHz) is widely used in medicine (e.g., organ imaging), in the electronics industry (non-contact sensors) and in nature (e.g., echolocation in bats) [10]. In the case of potatoes, the key challenge of processing is to control the content of reducing sugars, which at high temperatures participate in Maillard reactions, leading to undesirable browning of chips and deterioration of taste [6,11–13]. Previous studies indicate that the accumulation of sugars is influenced by genetic factors, abiotic stress (water, thermal) and storage conditions [6,13–15]. Traditional methods of modifying these parameters are often based on chemicalization, which is contrary to the trend of sustainable agriculture. Ultrasound is a versatile, sustainable and economical technology widely used in food processing for operations such as filtration, freezing, frying, sterilization or cutting. As an alternative, a non-thermal method increases efficiency, extends shelf life and preserves nutrients, while improving physicochemical and sensory properties of food [8,9,14,17,18]. Darsana and Sivakumar [10] emphasize the key applications of ultrasonics as pre-processing and treatment methods in various food sectors. A novel approach to the production of chips is the use of ultrasonics in the prevention of processing defects. Low-frequency ultrasound (20–300 kHz) can modify plant metabolism, including the expression of genes related to sugar synthesis [11,14,17]. In the food industry, this technology is already used to improve the color and texture of fried products due to cavitation effects that occur in an aqueous environment [3]. In this study, sonication of potato tubers was used as a pre-planting treatment to assess its effect on the reduction of reducing sugar content, sensory quality of chips (color, texture, lack of discoloration, etc.). Hence, the main objective of this study is to assess the potential of ultrasonic treatment of potato tubers before planting as an innovative method of improving the quality of raw material for the agri-food industry, with particular emphasis on its impact on the processing suitability of potatoes and the sensory quality of derived products, such as chips, in the context of reducing the use of pesticides in modern agriculture.

The alternative hypothesis (H1) assumes that ultrasonic treatment of potato tubers before planting will improve the quality of the raw material for food processing, specifically by reducing the reducing sugar content of harvested potatoes and improving the sensory characteristics (such as lighter color, better texture, and fewer defects) of chips produced from these potatoes compared to tubers not subjected to ultrasonic treatment.

Null hypothesis (H0): Ultrasonic treatment of potato tubers before planting will have no significant effect on the quality of the raw material for food processing, including the reducing sugar content of harvested potatoes or the sensory attributes (such as color, texture, and defect rates) of chips produced from these potatoes.

2. Materials and Methods

A strict field experiment in three replications in a dependent design, split-split-plot, was conducted in 2015–2017 at the Experimental Variety Testing Station in Uhnin (51°34' N, 23°02' E,

h=155 m a.s.l.), in southeastern Poland. The first-order factor was two technologies: Traditional without the use of ultrasound (control) and technology using ultrasound as a pre-planting treatment. The second factor of the experiment was eight edible varieties from four earliness groups; (very early: ‘Denar’ and ‘Lord’; early: ‘Owacja’ and ‘Vineta’; medium early: ‘Satina’ and ‘Tajfun’; medium late: ‘Syrena’ and ‘Zagłoba’).

2.1. Field Research

The field experiment was conducted in accordance with the methodology of research on the economic values of varieties in force at the Research Centre for Cultivar Testing (COBORU) in Experimental Stations [19]. The potato pre-crop was spring cereal (spring barley). Tubers were planted in the third decade of April at a spacing of 67.5 x 37 cm, the harvest plot was 15 m², i.e., 60 potato plants were planted in two rows of 30 tubers, in three replications. Standard NPK fertilization was applied; 90 kg N, 90 kg P₂O₅ and 135 kg K·ha⁻¹. After planting the tubers, segetal vegetation was controlled using mechanical and chemical methods, while potato pests and early and late potato blight (*Alternaria solani* and *P. infestans*) were controlled in accordance with the principles of good agricultural practice [20]. Potato tubers were harvested at the 99° BBCH scale [21]. During harvest, 20 tubers (10 pieces with dimensions of 51–60 mm and over 60 mm) with a shape typical for a given variety, without visible external deformations and greening, were taken from each field experiment replicate, intended for testing chips [19]. In addition, 5.5 kg of tubers were taken from each plot during harvest to determine the content of soluble and reduce sugars [22]. In technology with the use of ultrasound, before planting, potato tubers were subjected to the sonication process in a water environment at a temperature of 18 °C for 10 minutes. The time of ultrasound exposure was determined in pilot studies, longer exposure of the potato tuber to ultrasound damaged its ability to germinate. The sonication process was carried out in a tank device equipped with three piezoelectric ultrasonic transducers attached to the bottom of a tank made of acid-resistant steel (Figure 1). The transducers generated ultrasonic waves and were powered by an alternating current of 50 Hz and an output power of 200 W, in accordance with the Polish Standard PN-IEC 6003 [23]. Potato tubers grown in traditional technology were soaked for 10 minutes in distilled water to create an environment similar to that prevailing in the case of ultrasonic treatment, in order to eliminate the effect of water on the physiology of potato emergence.

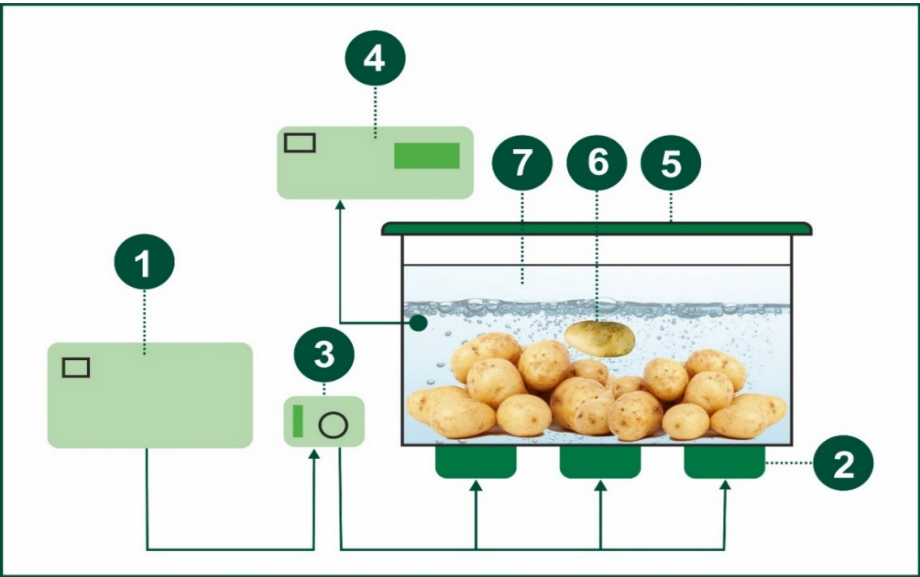


Figure 1. Ultrasound processing setup diagram: 1—ultrasound generator, 2—ultrasound transducer, 3—time controller, 4—thermometer, 5—tank with lid, 6—sample, 7—water. Source: own.

2.2. Characteristics of Potato Varieties

The experiment tested edible potato varieties with an established position on the consumer market [24]. The potato varieties tested showed a range of characteristics related to tuber flesh color, culinary type, flavors, starch content and harvest time. While all varieties had yellow skin, their flesh color ranged from light yellow (for 'Denar', 'Lord' and 'Owacja') to yellow (for 'Vineta', 'Satina', 'Tajfun', 'Syrena' and 'Zagłoba') [19].

Culinary classifications also varied: 'Denar', 'Lord' and 'Vineta' were AB type; 'Satina', 'Syrena' and 'Zagłoba' were B type; and 'Owacja' and 'Tajfun' had B-BC flesh [19]. Flavor assessment was generally consistent for most varieties, scoring 7 out of 9. However, the 'Satina' variety was rated slightly higher, at 7.5, which indicates slightly better taste quality than the others [19].

Starch content varied significantly, from 12.3% to 16.5%. 'Tajfun' (16.5%) and 'Syrena' (15.4%) showed the highest starch level, followed by 'Owacja' (13.5%) and 'Vineta' (13.7%). The lowest starch content was found in tubers of the 'Denar' (12.3%), 'Lord' (12.4%), 'Zagłoba' (12.6%) and 'Satina' (12.8%) varieties [19].

The date of potato harvest was related to the maturity groups of the varieties: very early varieties ('Denar', 'Lord') were harvested in the first ten days of September; early varieties ('Owacja', 'Vineta') in the second ten days of September; medium-early varieties ('Satina', 'Tajfun') in the third decade of September; and medium-late varieties ('Syrena', 'Zagłoba') in the first decade of October. This diversity of features highlights the adaptability and diverse culinary potential of the potato varieties studied [19].

2.3. Laboratory Tests

2.3.1. Chips Rating

The tubers intended for chips were peeled and then cut into 1.0-1.5 mm thick slices. They were then rinsed with cold water to rinse out free starch and dried. The chips were fried by the single stage frying method in vegetable oil heated to 170°C for 3-4 minutes until the moisture content dropped below 2% (Figure 2). Immediately after frying, the color, taste and general appearance of the products as well as their defects, i.e., discoloration and so-called wet spots, were assessed. The color of the chips was assessed on a 9° scale using the "Cards color" table developed by the European Potato Research Association in Wageningen, where 9° – light color; 8° – gold color; 7° – light gold color; 6° – dark gold color; 5° – brown-gold color; 4° – brown color; 3° – dark brown color; 2° – brown color; and 1° – burnt, brown-black color. The desired color of the chips was in the range of 6–9° on a 9° scale. In addition, the visual and organoleptic evaluation of the chips was performed on a 5-point scale, where 5.0–4.5° means a very good result; 4.4–4.0° – good; 4.0–3.0° – satisfactory; 3.0–1.0° – unsatisfactory [25]. The visual, taste, and smell evaluation of the chips was performed by a trained and experienced 10-person team meeting the formal and consumer requirements for the organoleptic and rheological evaluation, in accordance with the EN ISO 8586 standard [26]. Each analysis was performed in 10 replicates.



Figure 2. Chips production stages: a) cutting, b) drying, c) appearance in the fryer, d) frying in an electric fryer

2.3.2. Determination of Sugars

Technique: Iodometric Luff-Schoorl method with modification [27]. Standards: Glucose standard solutions were used for calibration. Sample preparation: Fresh potato tubers were homogenized and extracted in distilled water (80°C, 30 min). The extract was clarified by filtration and diluted to volume. For each sample, three independent replicates (n=3) were prepared.

Analytical procedure:

- The following were introduced into the volumetric flask: 10 mL of Luff solution
- 25 mL of sample.
- The mixture was heated for 10 min in a water bath ($95 \pm 2^\circ\text{C}$). After cooling, 10 mL of KI (10%) and 25 mL of H_2SO_4 (25%) were added.
- Iodine was determined titrimetrically with sodium thiosulfate (0.1 M) against starch.

Calculations: Sugar content was expressed as:

$$\text{Reducing sugar [\%]} = \frac{(V_0 - V) \times c \times k \times 100}{m}$$

where: V_0 —blank volume, V —sample volume, c — $\text{Na}_2\text{S}_2\text{O}_3$ concentration; k —conversion factor; m —sample mass.

- Quality control: Each series was analyzed for:
- Blank.
- Positive control (glucose solution).
- $\text{RSD} < 5\%$ was assumed for replicates.

Results are expressed as mean $\pm$ SD of three replicates.

2.3.3. Fat Content Determination

The fat content in the chips was determined using the Soxhlet extraction method—gravimetric, while the moisture content was measured gravimetrically [28]. Procedure: A sample of chips (5-10 g) was homogenized and pre-dried at 105°C. Extraction with an organic solvent (petroleum ether) for 6-8 cycles. Then, the solvent was evaporated, and the extract was dried to a constant mass. The result was expressed as a percentage of fat content in relation to the sample mass [28]. The advantage of this method was high accuracy and good repeatability (RSD < 2%).

2.3.4. Moisture Content Determination

Moisture content determination was performed using the thermogravimetric method (drying to constant mass). Procedure: An accurately weighed sample (2-5 g) was dried at 105 ± 2°C for 4-5 hours. Cooling was performed in a desiccator, and the samples were weighed again. This procedure was repeated until a constant mass was obtained (difference < 0.5 mg between weighing's). The result was calculated as a percentage loss in mass. The advantages of this method were simplicity of execution, low cost, RSD ~1-1.5% [28].

2.4. Soil Conditions

The experiment was located on a brown soil, developed from sandy loam, belonging to a very good rye complex, quality class IVa [29]. The tested soil was characterized by proper pH and high content of most nutrients, however: Low humus content could limit water and mineral retention; Variable potassium content (the lowest in 2016) could affect yield in drier years; High zinc and boron content was beneficial for tuber quality, especially in the production of chips. These data suggest that the soil was sufficiently fertile, but in dry years it could require additional irrigation or potassium fertilization. High phosphorus and magnesium content minimizes the risk of deficiencies of these nutrients [30].

Table 1. Content of available forms of phosphorus, potassium and magnesium and some microelements, content of humus and soil acidity before establishing the experiment in 2015-2017.

Year of research	Content Macronutrients			Humus content [g kg ⁻¹]	pH [KCL]	Micronutrients content				
	[mg kg ⁻¹ soil]					[mg kg ⁻¹ soil]				
	P	K	Mg			Cu	Mn	Zn	Fe	B
2015	8.9	10.9	7.8	0.94	5.9	7.51	318	40.1	3760	7.24
2016	8.3	9.1	7.0	1.06	5.8	4.92	337	56.7	3925	5.28
2017	10.6	9.8	6.3	1.03	6.6	8.99	166	41.1	3600	6.04
Mean	9.3	9.9	7.0	1.02		7.02	273.8	45.96	3761.7	6.17

Source: Analysis in District Chemical and Agricultural Station in Lublin.

2.5. Meteorological Conditions

Meteorological conditions in the study years were varied (Table 2).

Table 2. Total rainfalls and average air temperature during the growing season of potato according to the meteorological station in Uhnin 2015-2017.

Year	Month	Rainfall [mm]			Month	Air temperature [°C]			
		Decade				Decade			Mean
		1	2	3		1	2	3	
2015	April	14.6	5.9	41.3	61.8	5.4	8.6	12.4	8.8
	May	23.4	13.9	83.0	120.3	12.6	12.0	13.7	12.8
	June	5.4	16.5	24.8	46.7	17.7	16.3	16.1	16.7
	July	10.5	21.6	13.1	45.2	19.6	18.7	19.9	19.4

	August	0.4	0.00	5.7	6.1	23.4	20.6	20.3	21.4
	September	32.4	32.6	65.2	130.2	16.0	17.7	12.8	15.5
	Total				410.3				
2016	April	11.5	22.2	13.4	47.1	10.9	10.1	9.0	10.0
	May	4.9	2.8	38.6	46.3	14.4	17.8	12.9	15.3
	June	10.1	43.2	34.0	87.3	16.6	17.5	23.0	19.1
	July	22.4	30.8	60.9	114.1	19.5	20.1	21.9	20.5
	August	22.8	17.7	0.5	41.0	20.7	17.1	20.4	19.5
	September	7.6	0.10	4.1	11.8	19.5	15.5	11.5	15.5
	Total				347.6				
2017	April	6.4	7.2	38.2	51.8	10.6	6.8	6.9	8.1
	May	45.1	1.3	19.1	65.5	10.5	13.0	17.4	13.7
	June	1.9	9.2	12.0	23.1	16.6	17.7	20.7	18.3
	July	10.1	80.9	41.0	132.0	17.9	19.0	21.0	19.4
	August	0.4	24.4	2.2	27.0	22.8	21.3	17.1	20.3
	September	38.7	35.9	8.7	83.3	16.3	15.3	12.8	14.8
	Total				382.7				

Source the meteorological station in Uhnin.

The highest rainfall total in the three-year study cycle, during the potato vegetation period, was recorded in 2015. However, the rainfall distribution in this period was not conducive to the accumulation of tuber yield per unit area. During the period of intensive potato plant growth, during the accumulation of tuber yield, in the period June–August, a significant rainfall deficit was observed. September turned out to be very humid and very warm (2.8°C) above the multi-annual average, but the rainfall of this month was no longer decisive for the tuber yield [Table 2]. 2015 was the wettest season (HTC=1.7), especially in May (HTC=3.1) and September (HTC=2.8), but August was exceptionally dry (HTC=0.1) [31]. The lowest total rainfall, but with a favorable distribution of rainfall during the potato vegetation period, was recorded in the second year of the study (2016), and this year turned out to be very warm. Water shortages were recorded only in August and September, in which the total rainfall was only 60% of the multi-annual average with an air temperature higher than normal by 1.7°C (Table 2). The year 2016 was characterized by balanced to dry conditions (HTC=1.3), and July was the wettest month (HTC=1.9) [31]. 2017 was characterized by variable meteorological conditions. April turned out to be very humid, in May the optimal amount of rainfall was recorded, while in June a significant deficit was observed, only 33% of the multi-annual average and was also characterized by an average air temperature higher by 1.5°C. The rainfall balance improved only in July; a rainfall deficit was recorded again in August (Table 2). The year 2017 showed high variability of the hydrothermal coefficient—July was very wet (HTC=2.3), while June and August were dry (HTC=0.4) [31].

2.6. Statistical Calculations

The obtained research results were subjected to statistical analysis based on three-way ANOVA models [32] and Tukey’s multiple T tests, with the assumed significance level of $\alpha = 0.05$. Letter indicators at means (significance groups) designate so-called homogeneous groups (statistically homogeneous). The occurrence of the same letter indicator means at least one) means no statistically significant difference between them. The significance of the sources of variation was assessed using the Fisher–Snedecor F test, which is responsible for the proportion of variation resolved by each factor in relation to random variation [33]. The ANOVA model generates main effects, as well as two-way interactions between the analyzed factors, considering statistical significance [33]. Additional calculations of effect sizes (e.g., partial eta-square) for the quantitative purpose of practical significance of different functions. The application of Tukey’s test expansion on the detailed mean expansion, effectively identifying statistical differences in groups. Between them were considered important only if they were expanded, significant weight (LSD), considering the difference between

treatment methods. Multiple comparison of comparisons to achieve health indicators. Tukey’s study results study allowed detailed comparative analysis and definition of characteristic groups; thus, a solid statistical framework is available for the results and between the studied factors. Confidence divisions for other means were reported for the interpretation of interpretability and additional reliability [33]. In addition, descriptive statistics and simple correlation analysis were presented using the IBM SPSS Statistics program [34], which is used for data analysis, statistical description, explanation of phenomena, prediction and hypothesis testing.

3. Results

3.1. Evaluation of the Quality of Chips

The use of ultrasound as a pre-planting treatment in potato cultivation contributed significantly to the improvement of the quality of chips in such parameters as: color, visual evaluation, organoleptic evaluation, in relation to chips made from tubers obtained using traditional cultivation technology (Table 3).

Table 3. The influence of cultivation technology, varieties and years on the quality of chips.

Experimental Factors		Chips evaluation parameters		
		Color on a 9° scale	Visual assessment on a 5° scale	Organoleptic evaluation on a 5° scale
Technologies	Traditional	6.79 a*	3.60 a	3.72 a
	Ultrasounds	7.50 b	4.18 b	4.22 b
Varieties	‘Denar’	5.94 a	3.33 ba	3.44 ba
	‘Lord’	6.34 ba	3.06 a	3.31 a
	‘Owacja’	6.42 ba	3.28 ba	3.08 a
	‘Vineta’	7.96 d	4.50 d	4.53 d
	‘Satina’	7.28 c	3.94 c	4.0 c
	‘Tajfun’	8.36 d	4.72 d	4.78 d
	‘Syrena’	8.17 d	4.61 d	4.81 d
	‘Zagłoba’	6.70 bc	3.69 bc	3.83 bc
Years	2015	7.69 c	4.11 c	4.34 b
	2016	6.53 a	3.68 a	3.75 a
	2017	7.22 b	3.89 b	3.82 a
Mean		7.15	3.89	3.97

* The letter indexes accompanying the arithmetic meaning represent so-called homogeneous groups. The occurrence of the same letter index for at least one of the means indicates the lack of a statistically significant difference between them. The subsequent letter indexes a, b, c. define groups of means in ascending order.

The genetic properties of the tested varieties significantly modified the discussed features of the chips. The lightest color of the chips, the highest visual assessment and the highest organoleptic assessment were noted for chips made from the following varieties: Tajfun’, Syrena’ and ‘Vineta’, which were placed in one homogeneous group. The darkest color was noted for chips made from tubers of the ‘Denar’ variety, while the lowest visual assessment on a 5° scale was obtained by chips made from tubers of the ‘Lord’ variety, this variety also had the lowest organoleptic assessment, similarly to chips made from the ‘Owacja’ variety (Table 3). Meteorological conditions in the years of the study significantly modified the desired quality parameters of the chips. The agrometeorological conditions of the first year of the study, which was characterized by a deficiency of rainfall, significantly contributed to obtaining chips with the lightest color and at the same time obtained the highest visual and organoleptic assessments, in relation to the other years of the study. In the rainy year of 2016, the darkest chips were obtained, and they were characterized by the lowest visual and organoleptic assessments (Table 3).

The applied cultivation technologies had a significant effect on discoloration, the share of wet spots and fat content in the chips but did not affect the moisture content of this product. The use of ultrasound technology contributed to reducing discoloration by half, as well as a significant reduction in wet spots and lower fat absorption by the chips (Table 4).

Table 4. The influence of cultivation technology, varieties and years of cultivation on chips defects and fat content in chips.

Experiment Factors		Chips evaluation parameters (%)			
		Discoloration	Humidity	Moist areas	Content of fat
Technologies	Traditional	9.35 b*	2.19 a	3.43 b	28.25 b
	Ultrasounds	4.64 a	2.28 a	1.78 a	27.27 a
Cultivars	'Denar'	6.17 ba	2.44 ab	1.72 abc	24.30 a
	'Lord'	19.61 c	3.19 b	5.67 e	25.30 ab
	'Owacja'	9.83 b	2.16 ab	3.11 dbc	25.90 b
	'Vineta'	2.44 a	1.92 a	0.28 a	26.75 b
	'Satina'	8.61 b	2.26 ab	4.78 de	27.48 b
	'Tajfun'	2.78 a	1.96 a	0.56 a	29.42 b
	'Syrena'	2.72 a	1.87 a	0.83 ab	31.25 b
	'Zagłoba'	3.78 a	2.08 ab	3.89 dec	31.68 b
Years	2015	2.88 a	1.90 a	0.60 a	27.06 a
	2016	8.92 b	2.13 ab	3.27 b	27.81 a
	2017	9.19 b	2.68 b	3.94 b	27.62 a
Mean		6.99	2.24	2.60	26.39

* Designations as in Table 3.

Genetic features proved to be a factor significantly influencing all the tested defects and fat content in the chips. The lowest fat content was recorded in chips made from tubers of the 'Lord' and 'Denar' varieties, the remaining varieties had a similar fat content and were in the same homogeneous group (Table 4). The homogeneous group with the lowest share of discolored chips were the varieties: 'Vineta', 'Syrena', Tajfun' and 'Zagłoba'. Chips made from these varieties, except for the 'Zagłoba' variety, were also characterized by the lowest moisture content. Chips made from tubers of the 'Vineta' and 'Lord' varieties had the fewest moist spots and generally had the worst quality parameters. They were characterized by the highest share of discolouration, the highest moisture content and the moistest spots (Table 4). Chips obtained in the first year of the study, in which a significant water deficit was noted, were characterized by the best parameters. They had the least color, were the least moist and had the fewest moist spots, compared to the other years of the study (Table 4).

3.2. Content of Total Sugars and Reducing Sugars

The study of the content of total sugars and reducing sugars in tubers of different potato varieties allows for the assessment of their suitability for processing, especially for the production of chips and French fries (Figure 3).

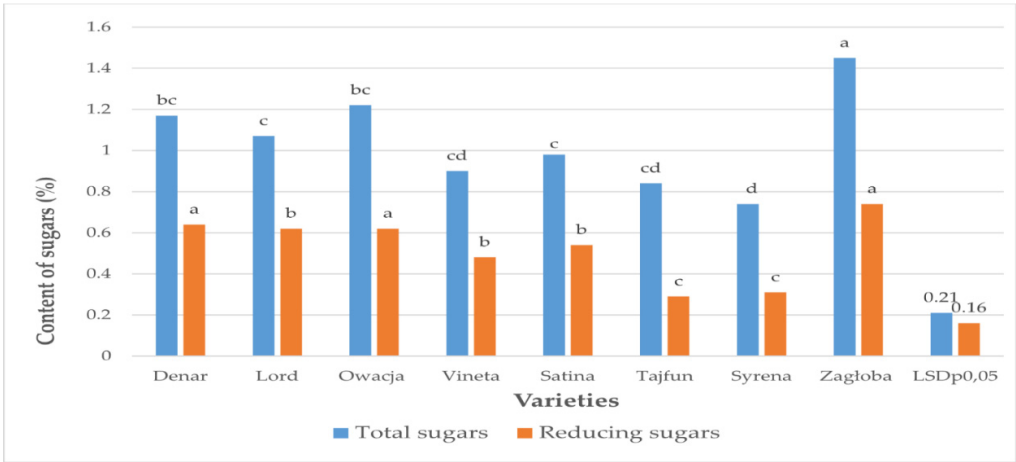


Figure 3. The influence of cultivars on the content of total sugars and reducing sugars in potato tubers.

The total sugar content in the analyzed varieties ranged from 0.74% ('Syrena') to 1.45% ('Zagłoba'). The highest value of this feature was recorded for the 'Zagłoba' variety (1.45%), while the lowest sugar content was characteristic of 'Syrena' (0.74%). A relatively high level of total sugars may affect the sweet aftertaste of the tubers and their behavior during heat treatment (Figure 3). Reducing sugars play a key role in the frying process because they affect the intensity of the Maillard reaction, responsible for the browning of chips and French fries. The 'Tajfun' variety had the lowest content of these sugars (0.29%), which makes it a very good candidate for processing. The 'Syrena' (0.31%) and 'Vineta' (0.48%) varieties were also characterized by a low content of reducing sugars, which favors their use in the production of chips. The highest value of this feature was recorded for the 'Zagłoba' variety (0.74%), which may result in excessive darkening of the chips during frying (Figure 3).

The tested varieties differed significantly in the content of reducing sugars. Four varieties were in two homogeneous groups. The first group included the varieties 'Tajfun' and 'Syrena', the second group included the varieties 'Lord' and 'Owacja' with a content of 0.62%, the remaining varieties accumulated a varied content of these sugars in the fresh mass of tubers (Figure 3). For varieties intended for the production of chips, the key criterion is the low content of reducing sugars (below 0.5%). The varieties that met these criteria were 'Tajfun', 'Syrena' and 'Vineta'. The variety on the border of acceptability was the medium-late 'Satina' (0.54%). The varieties less suitable for this type of processing were: 'Denar', 'Lord', 'Owacja' and 'Zagłoba'. The high content of reducing sugar increases the risk of excessive browning during frying.

The best suited for potato processing were the varieties 'Tajfun', 'Syrena', 'Vineta' and 'Satina', which have the lowest values of reducing sugars. Varieties such as 'Zagłoba', 'Denar' or 'Owacja' may not be suitable for this purpose due to the increased level of reducing sugars, which would result in undesirable darkening of the final products.

The technologies used did not have a significant effect on the content of reducing sugars. Only in the second year of the study, with the highest amount of rainfall, a significant decrease in the content of reducing sugars was observed in the objects where sonication of potato tubers was used before planting (Figure 4).

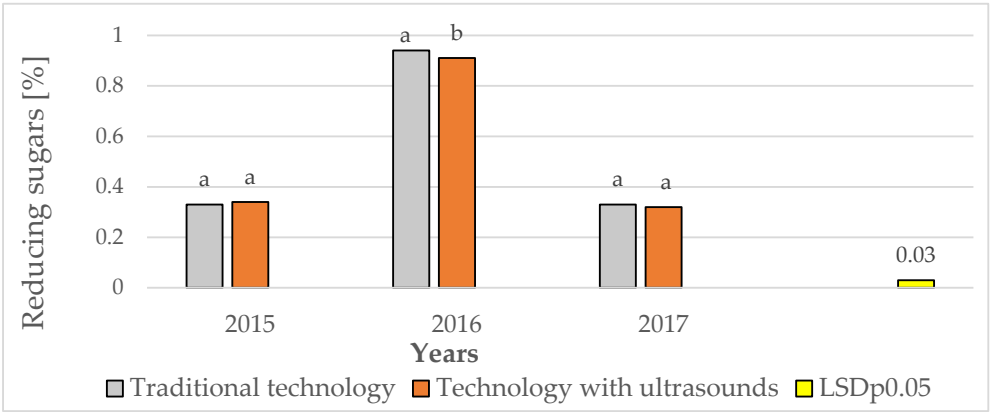


Figure 4. The influence of cultivation technology and years on the content of reducing sugars in potato tubers.

The genetic properties of the studied varieties in interaction with the variable conditions of the years of the study significantly influenced the content of reducing sugars in potato tubers. The best raw material for the production of chips was obtained in the first and last year of the study. The content of reducing sugars in the fresh mass of tubers in these years did not exceed 0.5%, except for the ‘Zagłoba’ variety. The first year of the study was characterized by a certain deficiency of rainfall, while the last year was characterized by both excess and deficiency of rainfall. In the second year of the study, no significant differences were noted between the varieties. Most varieties accumulated more than 1.0% of sugars in the fresh mass of tubers this year. Only two varieties, Syrena’ and ‘Tajfun’, slightly exceeded their permissible limit (Figure 5).

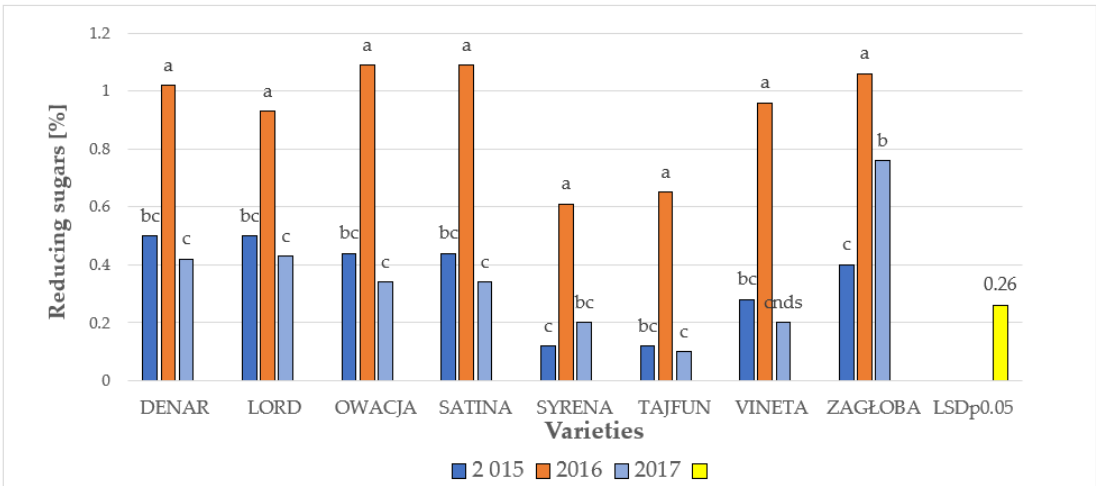


Figure 5. The influence of varieties and years on the content of reducing sugars in potato tubers.

The applied technologies in cooperation with the genetic properties of the tested varieties in most cases did not have a significant effect on the content of reducing sugars in potato tubers. Only a tendency to their lower accumulation was observed under the influence of sonication of tubers. In two cases: in the ‘Denar’ variety, a significant increase in the content of reducing sugars was noted in the object where ultrasound was used in comparison to the traditional technology. In the second case, in the ‘Vineta’ variety, the opposite process was observed, i.e., the applied ultrasonics contributed to a significant decrease in the content of reducing sugars in the fresh mass of tubers, in comparison to the traditional technology (Figure 6).

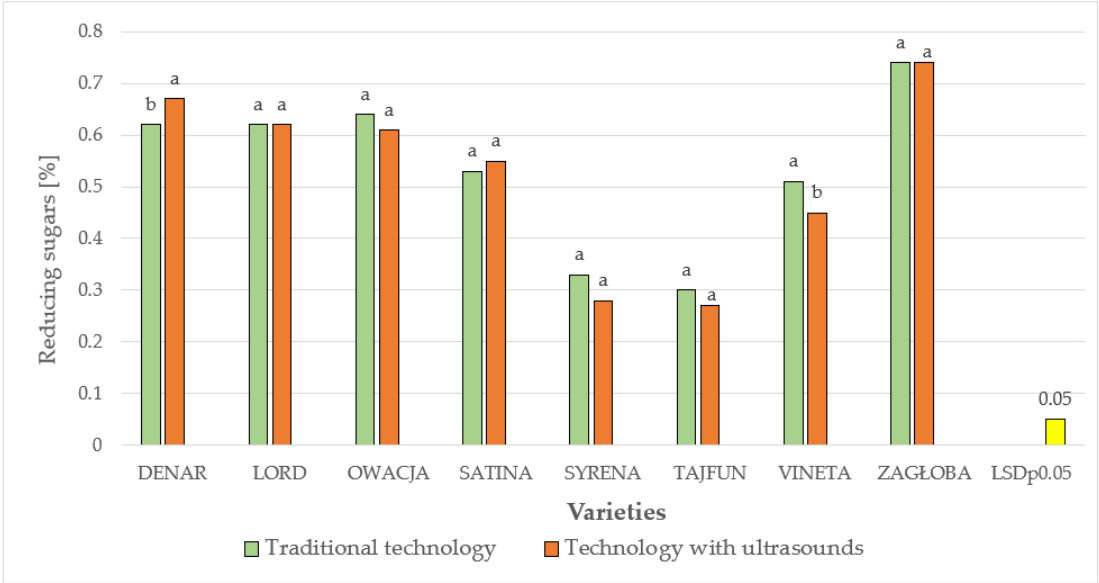


Figure 6. The influence of cultivation technology and varieties on the content of reducing sugars in potato tubers.

3.3. Multivariate Statistical Analysis of Quality Characteristics of Potato Chips

Descriptive statistics of the chips and some characteristics of the raw material for chips production, such as sugar content, are presented in Table 5.

Table 5. Descriptive statistics of the characteristics of chips and sugar content in the raw material for the production of chips.

Specification	y1	x1	x2	x3	x4	x5	x6	x7	x8
Average	7.15	3.89	3.97	2.24	6.99	2.60	27.59	1.05	0.53
Median	7.40	4.00	4.00	2.00	5.00	0.00	27.01	0.72	0.46
Standard deviation	1.41	0.92	0.93	1.24	9.76	4.11	2.69	0.76	0.33
Kurtosis	-0.72	0.18	0.27	78.76	7.50	3.96	-1.37	-1.10	-1.08
Skewness	-0.51	-0.71	-0.73	7.76	2.53	1.89	0.28	0.65	0.48
Range	5.20	4.00	4.00	14.00	50.00	20.00	7.99	2.41	1.06
Minimum	3.80	1.00	1.00	1.00	0.00	0.00	24.01	0.18	0.09
Maximum	9.00	5.00	5.00	15.00	50.00	20.00	32.00	2.59	1.15
Variation coefficient V (%)	19.71	23.54	23.29	55.52	139.52	157.79	9.74	72.86	63.15

y1—color of chips on a 9° scale; x1—visual assessment of chips on a 5° scale; x2—organoleptic assessment of chips on a 5° scale; x3—moisture content of chips in %, x4—defects and discolourations of chips in %; x5—moist spots in chips in %; x6—fat content in chips in %; x7—total sugar content in % of the fresh weight of tubers; x8—reducing sugar content in % of the fresh weight of tubers.

Color and sensory evaluation of chips (y1, x1, x2). The average color value of chips (y1) was 7.15 on a 9-point scale, which suggests a good color for the final product. Both the visual evaluation (x1) and the sensory evaluation (x2) of chips oscillated around the value of 3.89–3.97 on a 5-point scale, which indicates a very high sensory quality of this product (Table 6). The coefficients of variation for these features (approx. 23%) indicate a moderate sample variability, which in turn suggests a relative homogeneity of the material (Table 5).

Product moisture and its defects (x3, x4, x5). The moisture content of chips (x3) was on average 2.2% and showed high variability (V = 55.5%) and extreme deviation (max. 15%), which suggests significant differences in the water content of the raw material for chips production (Table 5).

Table 6. Pearson’s simple correlation coefficients of chips characteristics.

Specification	y1	x1	x2	x3	x4	x5	x6	x7	x8
y1	1.00								
x1	0.87	1.00							
x2	0.78	0.88	1.00						
x3	-0.14	-0.25	-0.26	1.00					
x4	-0.62	-0.71	-0.67	0.18	1.00				
x5	-0.38	-0.54	-0.58	0.20	0.67	1.00			
x6	0.34	0.38	0.43	-0.20	-0.30	-0.11	1.00		
x7	0.44	-0.29	-0.28	-0.06	0.18	0.17	-0.04	1.00	
x8	-0.54	-0.38	-0.37	0.01	0.22	0.19	-0.17	0.94	1.00

y1—color of chips on a 9^o scale; x1—visual assessment of chips on a 5^o scale; x2—organoleptic assessment of chips on a 5^o scale; x3—moisture content of chips in %, x4—defects and discolourations of chips in %; x5—moist spots in chips in %; x6—fat content in chips in %; x7—total sugar content in % of the fresh weight of tubers; x8—reducing sugar content in % of the fresh weight of tubers.

Defects and discolorations (x4) and wet spots (x5) were characterized by the highest variability (V = 139–158%) and strong skewness and kurtosis, which indicates the presence of extreme cases (e.g., samples with no defects at all or with a high proportion of them). The average value of defects was 6.9%, and wet spots 2.6% (Table 5).

Fat content (x6). The average fat content in the chips was 27.59%, with a relatively low variability (V = 9.74%), which indicates a homogeneous frying process. Low kurtosis and moderate skewness suggest a distribution close to normal (Table 5).

Sugar content in tubers (x7, x8). The content of total sugars (x7) was on average 1.05% and reduced sugars (x8) 0.53% in the fresh weight of tubers. The high variability of these parameters (V = 73% and 63%, respectively) indicates significant differences between varieties, which is important because the content of reducing sugars strongly affects the intensity of darkening of chips during frying. Too high a content of these sugars (>0.5–0.6%) may lead to undesirable darkening of products (Table 5).

Most of the tested samples obtained high scores in the sensory evaluation, but the variability in the content of defects, spots and reducing sugars, which affect the final quality of chips, may be a major problem. The greatest threats to the quality of chips may be too high a content of reducing sugars in the tubers of some varieties and the presence of defects, which indicates the need for careful selection of varieties and optimization of the conditions of storage and processing of tubers.

3.4. Correlations Between Potato Chips Quality Parameters—Statistical Analysis

Table 6 with Pearson correlations shows the relationships (strength and direction of dependence) between various features assessed in the study of potato chips quality and sugar content in the potato raw material. The purpose of the table is to determine which factors affect the quality of chips—including their color, appearance, taste, fat and sugar content, as well as the occurrence of defects.

The correlation coefficient determines the level of linear dependence between random variables. The cooler of the chips was characterized by an excellent positive correlation with the visual assessment and the organoleptic assessment of the chips. On the other hand, the color of the chips was strongly negatively correlated with the defects and discolourations of the chips (-0.62) and the content of reducing sugars in the fresh mass of the tubers (-0.54) (Table 6). The visual assessment of the chips was highly positively correlated with the organoleptic assessment of the chips (0.88), and with a high negative correlation with the defects and discolourations of the chips (-0.71) and the number of wet spots on the chips (-0.54). The organoleptic assessment of the chips was also negatively correlated with the defects and discolourations of the chips and the number of wet spots on the chips; respectively (-0.67 and -0.58). Our own research shows that the defects and discoloration of chips go

hand in hand with the number of wet spots in the chip; this positive linear correlation, unfavorable in the production of chips, reached the value of (0.67) (Table 6).

Sensory evaluation and color of chips (y_1 , x_1 , x_2). There was a very strong positive correlation between the color of chips (y_1) and their visual evaluation (x_1), as well as between color and organoleptic evaluation (x_2) ($r = 0.78$). This means that the lighter and more uniform the chips, the better they were evaluated by tasters. The correlation between the visual and organoleptic evaluation of chips (x_1 and x_2) was also high ($r = 0.88$), which indicates their consistency in the perception of quality (Table 6).

Moisture content of chips (x_3). The water content in chips (x_3) shows a weak relationship or no correlation with other features—the greatest negative correlations, but still weak, occur with sensory evaluations (e.g., with x_1 : $r = -0.25$). This suggests that water content is not directly perceived by tasters and does not significantly affect the color or fat content of the chips (Table 6).

Defects and discolouration (x_4), damp spots (x_5). Defects and discolouration (x_4) were strongly negatively correlated with sensory scores and chip color ($r = -0.62$ to -0.71), clearly indicating that increased defects reduce the quality of the chips. Damp spots (x_5) also had a moderately strong negative correlation with sensory scores ($r = -0.54$ to -0.58) and were found to be moderately positively correlated with defects ($r = 0.67$), suggesting a common source of these undesirable features (e.g., technological or storage problems) (Table 6).

Fat content (x_6). Fat content (x_6) shows a moderate positive correlation with their sensory scores (e.g., $r = 0.43$ with x_2), which may suggest that chips with a higher fat content may be more acceptable in terms of taste and texture. At the same time, fat content did not correlate significantly with their moisture or with the sugar content of the raw material (Table 6).

Total sugars (x_7) and reducing sugars (x_8). The strong correlation between total and reducing sugars ($r = 0.94$) indicates their close interdependence, which is expected since reducing sugars are part of total sugars. Reducing sugars (x_8) were significantly negatively correlated with the color of the chips ($r = -0.54$) and sensory scores, confirming that higher levels of them lead to darkening of the chips and their deterioration (Table 6).

Table 6 allows us to understand which features are strongly related to each other and which do not have a significant effect on each other.

4. Discussion

4.1. The Effect of Sonification on Potato Metabolism and Chip Quality—Current Mechanisms and Practical Implications

Our own studies prove that ultrasonic waves activate metabolic processes in potato plants. In the conducted studies, based on pilot studies, the optimal time of sonication of tubers was assumed to be 10 minutes, which is consistent with the reports of Teixeira da Silva & Dobránszki [35], Guiné et al. [36], Kutlu et al. [3]. They state that the use of acoustic sound or ultrasound in extreme conditions with too high frequency or for long periods of exposure are harmful and even fatal to plants, while milder conditions of sonication can improve the growth or development of plants and affect the antioxidant system and hormonal balance of plants. The results of the studies by Antunes-Rohling et al. [37] confirm that ultrasonic treatment (US) significantly affects the properties of potatoes before frying, and optimal parameters can effectively reduce the content of acrylamide in chips. These authors showed that:

- The temperature of 42°C favors water absorption, especially at lower ultrasound powers, which may be due to partial denaturation of cell membranes facilitating diffusion.
- Extraction of reducing sugars is most effective at 35 kHz and 92.5 W/kg (31% reduction), which directly translates into a reduction of the Maillard reaction during frying.
- Changes in colorimetric parameters ($\downarrow L$, $\uparrow a$) confirm the relationship between US treatment and the reduction of non-enzymatic browning.

- A 90% reduction of acrylamide compared to untreated samples proves that sonication can be a key strategy in the production of healthier chips.

Practical implications:

Optimal parameters (35 kHz, 92.5 W/kg, 42°C) provide a double benefit: improved food safety (less acrylamide) and sensory quality (better color). Further optimization is necessary for process scaling, especially energy balance.

Our own research and reports by Kutlu et al. [3] indicate that the use of ultrasound significantly improves the color of chips, compared to traditional technology. The latest studies [9,38] prove that this effect results from: short-term activation of ROS pathways, leading to: increased activity of antioxidant enzymes (SOD, CAT), modulation of expression of genes related to carbohydrate metabolism; inhibition of non-enzymatic browning reactions by destabilization of polyphenol oxidase (PPO). At the same time, it has been shown that long-term exposure (>15 minutes) leads to degradation of cell membranes and unfavorable sensory changes [9].

4.2. The Effect of Potato Sonication on Sugar Metabolism

The sugar content in tubers is strongly dependent on genotype [14], and sonication does not significantly affect their level [38,39]. Genes related to carbohydrate metabolism: InvInh2 (invertase inhibitor)—regulates sucrose degradation; Usagi (UDP-glucose pyrophosphorylase)—a key enzyme in starch synthesis; Amyl (amylase gene)—control starch degradation [38].

The determination of reducing sugars in potatoes is crucial for the quality of processed products. Due to the high genotypic variability, Pera-za-Alemán et al. [39] developed predictive models using near-infrared hyperspectral imaging (NIR-HSI). The best model (SNV-PLSR) achieved R²=0.88 (calibration) and 0.86 (validation), and variable selection algorithms (CARS, iPLS) reduced the number of wavelengths to 2.65–3.57% without losing accuracy. The visualization of sugar distribution at the pixel level confirms the usefulness of NIR-HSI in assessing the quality of raw material for chips production. The sugar content in potato tubers is strongly genotype-dependent [14], and sonication does not significantly alter their levels [38]. Key factors influencing sugar accumulation include (Table 7):

Table 7. Key Factors Influencing Sugar Accumulation in Potato Tubers and Their Impact on Processing Quality.

Factors	Effect	Source
Weather conditions	↑ in cold and humid periods	[40,41]
Storage temperature	Optimum: 6–8°C (↑ below 4°C & above 10°C)	[14,40,42]
Harvest time	July harvest → 5× higher sugar content than August	[43]

Source: own.

According to industry standards [44], acceptable sugar levels are Chips: ≤1.5 g·kg⁻¹ (max. 2.5 g kg⁻¹), French fries: ≤2.5 g·kg⁻¹ (max. 5 g kg⁻¹).

Mechanisms of Chip Quality Improvement. The 9.5% improvement in color is attributed to: PPO inactivation via cavitation-induced protein denaturation [9]; Structural changes in tuber tissue: Increased porosity → faster water evaporation (↓ final moisture by 12%); Enhanced oil diffusion during frying [8].

Industrial Implications: Recent recommendations (Food Eng. Rev., 2023) highlight: Customizing sonication parameters based on: Cultivar (e.g., low-starch potatoes require shorter exposure); End-use (chips vs. fries vs. puree); Synergy with emerging technologies: Pulsed electric field (PEF), Low-temperature plasma treatment Antunes-Rohling et al. [37].

Future Research Directions: Further studies should focus on: Molecular mechanisms of potato response to acoustic stress, Optimization for different farming systems (conventional vs. organic), Integration with AI and NIR spectroscopy for raw material sorting [37].

Key Improvements: More concise and structured (bullet points, table for key factors).

- Stronger academic tone (precise terminology, passive voice where appropriate).
- Better readability (logical flow, clear cause-effect relationships).
- Consistent formatting (uniform units, proper citation style).

4.3. *The Effect of Ultrasonic Treatment on the Fat Content of Chips*

The results of the conducted studies indicate a significant relationship between starch content and chip quality. Studies by Zhang et al. [8] on structural modifications of starch induced by ultrasound and reduction of oil absorption during frying have shown, among others:

Morphological changes in starch: Erosion of the surface of starch granules under the influence of ultrasound (confirmed in microscopic studies) led to the formation of a more compact internal structure of chips. Reduced water mobility in the raw material for the production of chips after US treatment limits moisture migration during frying [8,45].

Modulation of physical properties of slices: Increased porosity while reducing the diameter of slices (by ~15-20% according to SEM measurements). This leads to the formation of a more uniform microstructure with a limited tendency to crack during heat treatment [8,45].

Mechanisms of fat absorption reduction: Modified starch structure creates a barrier limiting oil penetration (confirmed by NMR measurements), while faster water evaporation (up to 25% faster) promotes the formation of a surface layer inhibiting absorption. This in turn leads to reduced surface viscosity of the raw material for chips production (rheological measurements) [36,45,46].

This results in practical implications, such as:

- US treatment at 35-45 kHz for 5-8 minutes allows us to achieve a reduction of the final fat content by 18-22% [47].
- Synergistic effect with pre-blanching (additional 7-9% reduction) [45,46].
- Possibility to control the texture of the final product by modulating sonication parameters [8,36,46].

Development prospects for the production of chips are primarily:

- The need for optimization for different potato varieties (different starch content).
- Research on scaling the process with consideration of energy efficiency [46].
- Glucose content in tubers is usually 80.5–97.6% of the coefficient of variation V for the brightness of French fries and 88.4–94.2% for the brightness of potato chips.
- The critical range of glucose content for acceptable products in French fries and chips based on color values (L^* and a^*) is 12–22 mg/100 g and 8–14 mg/100 g, respectively, for the tested varieties [45].

4.4. *The Influence of Varieties on the Quality of Chips*

4.4.1. Key Parameters of Chip Quality

The latest studies confirm that chip quality is mainly influenced by reducing sugar content (the main factor of darkening in the Maillard reaction); dry matter, which determines the texture and chipiness of chips; starch content and its structure, which affects fat absorption; enzymatic activity (e.g., polyphenoloxidases responsible for browning) [14].

4.4.2. Best Varieties for Chip Production

According to the conducted research, the 'Tajfun' variety is still the leader, due to the low content of reducing sugars (<0.3%) and high dry matter content (>22%).

'Syrena'—is a variety with stable parameters even in unfavourable climatic conditions (lower accumulation of sugars with temperature fluctuations).

‘Vineta’—this variety can be recommended due to the uniform structure of the flesh, which limits uneven frying.

‘Satina’ variety—requires strict storage control, but new research indicates that appropriate storage conditions (4°C, humidity 90%) can maintain sugars at an acceptable level (<0.5%).

Varieties not recommended for chips processing: ‘Lord’ and ‘Owacja’—despite agrotechnical improvements, they showed high variability of sugar content, which makes quality control difficult. Variety ‘Zagłoba’, even with optimal storage, exceeds the permissible standards for reducing sugar content (>0.7%)

4.4.3. Indications for the Processing Industry

Recommendations for the Processing Industry in the Context of the Latest Knowledge:

Optimal Variety Selection: The Tajfun and Syrena varieties continue to demonstrate high reliability in terms of quality parameters of the raw material for the production of chips. However, in the light of ongoing climate change and new research [include the latest citations on the resistance of varieties to abiotic stresses, e.g., heat and water], Lenora and Adelina appear as promising alternatives, potentially demonstrating better tolerance to extreme growing conditions. Nevertheless, the recommendation of specific varieties should consider the latest results of field trials in different regions and years, assessing their yield and quality stability under changing conditions.

Monitoring of Storage Conditions: Close monitoring of storage conditions remains crucial. The latest research [citations on the effect of controlled atmosphere, humidity and temperature on the long-term quality of potatoes for processing] confirms that even varieties with the best quality potential can be degraded as a result of inappropriate temperature and humidity. It is worth considering the implementation of predictive systems based on modeling the impact of environmental conditions during the growing season on the optimal storage parameters of a given batch of raw material [7].

Integration of Advanced Measurement Technologies: Further and broader integration of fast and non-destructive measurement technologies, such as near-infrared spectroscopy (NIR) and hyperspectral imaging (HSI), is necessary for routine assessment of reducing sugar content and other key quality parameters of the raw material before processing. The latest achievements in artificial intelligence and machine learning enable the creation of more precise and efficient quality assessment systems in real time, which allows for optimization of the production process and minimization of losses.

Holistic Approach to Quality: The latest research [citations integrating the impact of variety, agrotechnics and storage on chip quality] confirms that variety is the foundation of chip quality, but its potential can only be fully exploited with the use of optimal agrotechnical practices (considering adaptation to climate change, e.g., precise irrigation, fertilization) and precise storage conditions. Progress in potato breeding, focused on traits useful for processing and resistance to abiotic stresses, must go hand in hand with the implementation of integrated quality management systems at every stage of the supply chain [7].

Implementation of Recommendations: Conscious and consistent implementation of the latest recommendations, based on solid scientific research and innovative technologies, is crucial for significant improvement of production efficiency, cost reduction, ensuring high and stable quality of chips and increasing consumer satisfaction in the face of dynamically changing climatic and market conditions.

4.5. Influence of Climatic Conditions on the Quality of Raw Material for Chip Production

4.5.1. Influence of Temperature during the Vegetation Period

Our own research and literature data [48–50] clearly indicate that warm summers (average daily temperature >20°C) contribute to a decrease in the content of reducing sugars in potato tubers (<0.4% for the Tajfun variety, <0.5% for the Syrena variety). At the same time, a higher dry matter content (>22%) has a positive effect on the chipiness of chips. A negative correlation ($r = -0.72$) between

temperature and sugar accumulation was confirmed. Conversely, cool summers (average daily temperature <15°C) result in an increase in the level of reducing sugars by up to 30–50% (e.g., up to 0.7% in the Satina variety), increasing the risk of uneven frying and darkening of chips as a result of the Maillard reaction.

4.5.2. Effects of Water Stress (Drought/Excessive Rainfall)

According to the findings of Parra-López et al. [51] and Sawicka and Pszczółkowski [15], drought (rainfall <300 mm/year) leads to an increase in dry matter, which is desirable from the point of view of the texture of chips. However, it induces the accumulation of reducing sugars (metabolic stress), especially in sensitive varieties such as Lord and Owacja. It is worth noting that drip irrigation can reduce the increase in sugars by up to 15–20%. The authors [15,16,51] emphasize that modern technologies, including remote sensing and artificial intelligence, play a key role in the effective management of water resources in agriculture, and precision irrigation is a commonly used digital strategy. In turn, excess rainfall (>500 mm/year) causes a decrease in dry matter content (<20%), which results in the production of soft and not very chipy chips. In addition, plant susceptibility to diseases (e.g., *P. infestans*) increases, which indirectly contributes to an increase in sugar content in the raw material.

4.5.3. Extreme Weather Phenomena

Analysis of data from our own research from 2015–2017 and studies [51] showed that heat waves (>30°C) inhibit tuber growth but paradoxically may lead to a decrease in the sugar content (due to accelerated conversion to starch). Nevertheless, the risk of tuber deformation increases, which negatively affects the uniformity of the chips produced. Early autumn frosts cause a rapid increase in the sugar level (even up to 1% in the Zagłoba variety), which forces earlier harvesting of late varieties.

4.5.4. Influence of Storage Conditions (Interaction with Meteorology)

The relationship between meteorological conditions during the growing season and optimal storage conditions has been confirmed by [12–14] and our own studies. Tubers from wet years require a lower storage temperature (3–4°C) to limit starch hydrolysis. On the other hand, tubers harvested in dry years tolerate storage at a higher temperature (6–8°C) better due to a lower risk of sugar accumulation [42,43]. In the context of climate change and the latest knowledge: Extreme Weather Events:

- Climate change is causing an increase in the frequency and intensity of extreme weather events, such as heat waves, droughts, floods, storms and hailstorms. Each of these events can negatively affect the yield and quality of the raw material through mechanical damage, water stress, root hypoxia and increased susceptibility to diseases and pests [6,14,17,40,41].
- Elevated CO₂ Levels: Increased atmospheric carbon dioxide concentration can modify plant physiology, often stimulating photosynthesis, but at the same time potentially reducing protein and micronutrient content (so-called dilution effect).
- Phenological Changes: Higher temperatures can accelerate plant development cycles, shortening the vegetation period, which can lead to lower yields and changes in the chemical composition of the raw material [17].
- Pest Spread: Climate change can promote the migration and increased activity of pests and pathogens, which indirectly worsens the quality of crops through damage and the need for more intensive plant protection. The observation regarding the 'Satina' variety is particularly important, which, despite its recognized stability in terms of reducing sugar content, may be susceptible to heat stress. Current knowledge in this area focuses on:
- Physiological Mechanisms: High temperatures during tuber formation and maturation accelerate respiration and starch metabolism. Under conditions of extreme heat stress, the rate

- of starch synthesis may be lower than its decomposition into simple sugars (glucose and fructose) and then sucrose. Additionally, heat stress may disrupt the activity of enzymes key to starch synthesis [6,16,17].
- Genotype-Environment Interaction ($G \times E$): Studies [6,15,16,40,41] confirm a strong interaction between genotype and environment. Potato genotype determines the chemical composition of tubers, including the potential content of dry matter, starch and sugars. However, environmental conditions such as temperature, soil moisture, sunlight or fertilization can significantly modify these values. The right proportion of starch and sugars is crucial for obtaining chippy, non-burning chips with the desired color. Some potato genotypes can accumulate the ideal amount of dry matter, starch and reducing sugars only in specific climatic conditions, which is confirmed by the results of the conducted research. In addition, genetics is largely responsible for the shape and size of potato tubers. The environment in which the tubers grow can also affect their uniformity. Uniform, shapely potato tubers are easier to cut into slices of equal thickness, which translate into even frying and better texture of chips. Some genotypes may be more susceptible to deformation in unfavorable soil conditions [7]. Dry matter content: Genotype and environment jointly affect the dry matter content of potatoes. Higher dry matter content usually means lower water content, which is desirable for chip production because it shortens frying time and reduces oil absorption, leading to chips and less greasy chips. Some varieties can only achieve high dry matter content under specific irrigation conditions [7,13,16,42]. Disease and pest resistance: Genetically determined resistance to diseases and pests is crucial for healthy tubers. However, pathogen and pest pressure can vary depending on the environment. A variety that is resistant in one region may be susceptible to another due to different climatic conditions favoring the development of specific pathogens. Healthy potato plants are essential for the production of high-quality chips [Zarzycka et al. 2021, Sawicka et al. 2021]. Both genotype and environment can affect the content of phenolic compounds, which can affect the taste and shelf life of chips. Some potato genotypes naturally have higher levels of these compounds, but their levels can be further modified by growing conditions such as water stress, salt stress, or sunlight [7]. In summary, studies confirming the strong interaction of genotype and environment in the context of potato chips suggest that there is no single “universally best” potato variety. The quality of chips depends largely on whether a given genotype is grown in its optimal environmental conditions. Chip producers, striving to obtain a product of high and stable quality, must consider this complex interaction, carefully selecting both potato varieties, their growing regions, and the agricultural practices used. The studies conducted provide concrete examples of how specific combinations of genotype and environment affect specific quality traits of chips.

4.6. Concordance of Sensory and Visual Assessment and the Impact of Quality Defects

This paper discusses key relationships between various quality assessment methods, emphasizing the high concordance between visual and sensory assessments. The impact of specific quality defects on both forms of evaluation is also presented, which has significant implications for product quality control.

The analysis demonstrated high concordance between visual and sensory assessments, as confirmed by the correlation coefficient ($r=0.88$). This strong correlation suggests that quality perception is consistent regardless of whether the product is assessed visually or through other senses (e.g., touch, smell, taste). This indicates that visual methods can be an effective predictor of overall sensory perception, which has practical applications in rapid and efficient quality control processes.

However, both visual and sensory assessments are biased by a number of factors related to product quality. Among other things, a negative correlation was found between the presence of defects and discoloration and quality assessment. This indicates that any visual defects, such as irregularities in color, shape, or texture, significantly reduce the perceived quality of the product.

The presence of moisture stains also negatively impacts perceived quality. The correlation coefficients were $r=-0.54$ for visual evaluations and $r=-0.58$ for sensory evaluations, respectively. Moisture stains may suggest improper storage or other issues that raise concerns about the product's freshness and safety.

General issues related to production quality negatively impacted both evaluation methods. References to the literature [8,47] suggest that these may be issues related to production processes, such as inconsistent workmanship, assembly errors, or non-compliance with specifications. These factors can affect the overall aesthetics and sensory experience, leading to lower quality ratings.

The importance of a comprehensive approach to quality control that considers both visual and sensory aspects is emphasized. Identifying and eliminating defects such as discoloration, moisture stains, and other manufacturing issues are crucial to maintaining a high level of perceived product quality. Further research could focus on the specific quality issues identified in the literature [8,47,52] and developing strategies to minimize their impact on consumer acceptance.

4.7. Research Perspectives

Integration of Meteorological Data and Tuber Quality Using Ultrasound in Predictive Models may concern the following aspects of research:

Extension of AI Models: Development of advanced predictive models based on artificial intelligence and multi-factor analysis, which will combine detailed meteorological data (temperature, precipitation, humidity, sunlight in different growth stages) with tuber characteristics (reducing sugar content, starch, dry matter, texture) and ultrasonic processing parameters. These models should consider the influence of different climatic conditions on the susceptibility of tubers to quality optimization using ultrasound.

Optimization of Ultrasonic Parameters: Study of the influence of different ultrasonic parameters (frequency, power, exposure time, medium temperature) used at different stages of the chip production process (e.g., before cutting, after cutting, before frying) on key quality indicators such as reducing sugar content, oil absorption, texture (chipiness, hardness), color and sensory properties of the finished product. Predictive models should assist in the selection of optimal ultrasound parameters depending on the characteristics of the raw material and meteorological conditions during its growth.

Assessment of Resistance of New Varieties to Abiotic Stress in the Context of Ultrasound Application:

Controlled Stress Conditions with Pre- and Post-Harvest Ultrasound Treatment: Testing the resistance of new and promising potato varieties to simulated abiotic stress conditions (e.g., drought, high temperatures in foil tunnels) with simultaneous assessment of the potential of ultrasound techniques to mitigate the negative effects of stress on the quality of raw material for the production of chips. The studies should include the application of ultrasound both before harvest (e.g., growth stimulation, improvement of resistance) and after harvest (e.g., reduction of reducing sugars, improvement of texture before processing).

Genotype-Environment-Ultrasound Interaction Analysis ($G \times E \times U$): Study of the interaction between genotype (variety), environment (stress conditions) and the use of ultrasonic techniques at different stages of chip production. The aim is to identify varieties that, under specific stress conditions, respond best to ultrasonic treatment in terms of improving the quality of chips.

Mechanisms of Ultrasound Action on Raw Material and Final Product Quality: Cellular and Molecular Level Studies: Detailed studies of the mechanisms of ultrasound action at the cellular and molecular level in potato tissue. The effect of ultrasound on the activity of enzymes responsible for sugar and starch metabolism, cell wall structure, cell membrane permeability and the release of phenolic compounds and other antioxidants should be studied. Understanding these mechanisms will allow for more informed and effective use of ultrasonic techniques.

Influence of Ultrasound on Chip Microstructure: Study of the effect of ultrasonic treatment on the microstructure of fried chips (porosity, cell structure) and its correlation with texture and oil absorption.

Optimization of Ultrasonic Process in Chip Production at Semi-Industrial and Industrial Scale: Scalability and Cost-Effectiveness: Investigation into the scalability and cost-effectiveness of using ultrasonic techniques in industrial production of chips. Optimal configurations of ultrasonic devices should be developed and integrated into existing production lines.

Life Cycle Assessment and Sustainability: Analysis of the life cycle and environmental impact of using ultrasonics in chips production, including energy consumption and potential benefits in terms of reducing oil consumption and improving product quality.

In summary, future research should focus on a holistic approach, integrating knowledge from agronomy, meteorology, genetics and food processing engineering. Exploitation of the potential of ultrasonic techniques, supported by predictive modeling and assessment of variety resistance, may open new possibilities for improving the quality of chips and increasing their production efficiency under changing climatic conditions.

4.8. The Study Identified a Particularly Problematic Relationship

A strong positive correlation ($r = 0.67$) existed between: The occurrence of defects/discolorations; The presence of moisture spots. This interdependence suggests this quality issues frequently co-occur during production, presenting a compounded challenge for manufacturers.

Technical Implications: The correlation patterns indicate that: Color measurement could serve as a reliable proxy for overall quality assessment. Reducing sugar content in raw materials significantly impacts final product appearance. Moisture control is crucial for minimizing multiple quality defects simultaneously

These findings provide quantitative support for focusing process improvements on:

- Raw material selection (reducing sugar content).
- Moisture management during processing.
- Color development monitoring [8,9,36].

The strength of these correlations (all statistically significant at $p < 0.05$) underscores their importance in industrial quality control systems.

Our own research shows that applied technologies had no significant effect on the level of soluble and reducing sugars and is consistent with the reports. The research of these authors shows that the comparison of conventional cultivation with integrated and ecological cultivation did not bring a positive conclusion about the dominance of any of them in relation to the content of reducing sugars. Also, the method of fertilization, with and without the use of manure, had no significant effect on their content. It resulted in the level of reducing sugars of the same potato variety harvested in July was five times higher than those harvested at the end of August. The results of the research of most authors [14,42] confirm unanimously that the earliness of varieties and the degree of maturity of tubers are of significant importance for the content of reducing sugars. Early varieties and those harvested at the stage of incomplete maturity have a higher level of reducing sugars during harvesting compared to medium-late varieties and those harvested at the stage of full maturity [42]. Our own research, in which eight edible varieties from different earliness groups were tested, confirms this view, a similar relationship results from the research by Zgórska and Grudzińska [42]. The research of these authors emphasizes the relationship; that the content of reducing sugars decreases with the increase in starch content in potato tubers. Very early and early varieties usually contain lower starch content compared to medium late and late varieties. Our own research proves that the use of ultrasound contributed to obtaining chips with a nicer color by 9.5% than chips produced from tubers obtained from the control object. Kutlu [3] reports that the effect of ultrasonic applications on food colors is quite positive, and the proper determination of the conditions of ultrasound application is very effective in preserving the color of food. Moreover, these researchers state that minimizing energy and power consumption while simultaneously preserving the color of

food is one of the directions of the processing industry. The conducted studies showed that the potato varieties studied differed significantly in terms of the content of total sugars and reducing sugars in tubers and contained on average 1.05% of total sugars and 0.53% of reducing sugars in fresh weight (Table 2). Grudzińska et al. [14] and Murniece et al. [18] showed that the content of reducing sugars is a feature directly related to the genotype of a given variety. In our studies with 8 potato varieties, the content of reducing monosaccharides ranged from 0.3 g·kg⁻¹ to 3.8 g·kg⁻¹ (Table 3).

According to [9,13,52], the content of total sugars above 10 g·kg⁻¹ in the fresh weight of tubers (glucose + fructose + sucrose) affects the change in the taste of boiled and fried tubers. These authors showed that the increase in saccharide content in tubers does not affect the appearance of their sweet aftertaste, however, tubers of very early and early varieties did not meet the criteria set for raw materials intended for the production of French fries and chips. The obtained results are consistent with the data presented by Zgórska and Frydecka-Mazurczyk [53], Gugała et al. [40]. These authors showed that extremely high sugar contents were caused by atmospheric conditions. In wet and cold periods, the sugar content in tubers was significantly higher than during optimal conditions. Different results were obtained by Grudzińska and Zgórska [14]. These authors proved that the content of reducing sugars in mature and immature tubers is similar and amounts to an average of 0.2 g·kg⁻¹ of fresh tuber mass. The lack of full maturity of tubers, manifested by high activity of invertase hydrolyzing sucrose to glucose and fructose, may indicate that even tubers characterized by harvest maturity, with properly developed skin and debarking of the stolon attachment, come from over-fertilized objects. According to Grudzińska et al. [14], in tubers intended for processing, stored at a temperature of 6-8°C, due to intensive respiration, the accumulation of sugars is small, however, the consequence of higher temperatures are intensive physiological processes and premature aging of tubers [54]. The limiting temperature at which increased accumulation of glucose and fructose occurs is 7°C. The reduction of reducing monosaccharides is the result of a "compromise" between low and high storage temperatures. At low temperatures, the development of pathogens is minimized, and metabolic processes are strongly inhibited, while at higher temperatures, the tubers metabolize intensively, but at the same time they are characterized by a low level of sugars. Sowa-Niedziałkowska and Zgórska [44] showed that the content of reducing sugars in potato tubers intended for French fries should not exceed optimally 2.5 g·kg⁻¹ (maximum 5 g·kg⁻¹ of dry matter) and for chips optimally 1.5 g·kg⁻¹ (maximum 2.5 g) of fresh mass. In turn, the content of total sugars should not exceed 10 g·kg⁻¹ of fresh mass in both cases. [44,48,55]. Too high sugar content is undesirable because it caramelizes during frying, which gives the products a brown color and a bitter taste [54]. According to Nawaz et al. [48], Mike et al. [49], Parra-López et al. [51], Lisińska [52,56], Zgórska and Frydecka-Mazurczyk [53] and Kahlil [57], if the dry matter content is higher than 25%, potatoes, especially those intended for the production of chips, will have a crispy structure.

4.9. Prospects for the Application of Ultrasonic Technology in the Potato Industry

Ultrasonic technology (20-100 kHz), generating cavitation with extreme pressure and temperature conditions [1-1], opens up innovative possibilities in potato processing.

Current research indicates three main areas of application:

1. Enzyme inactivation: Effective inhibition of polyphenoloxidase, preventing browning [56,57].
2. Sugar modulation: Effect on the metabolism of reducing sugars [14,18].
3. Immunity activation: Stimulation of natural plant defense mechanisms [2-4,17,35].

Structure improvement: Beneficial effect on potato tissue [2-5].

Reduction of discoloration: Reduction of undesirable color changes by 30-40% [3,8,10]. Increased efficiency by increasing the efficiency of thermal processes by 15-20%.

4. Sustainable development:
 - Reduced additives: Potential to reduce the use of antioxidants [3,8].
 - Chemistry: Potential to reduce the use of chemicals in cultivation [3,47].
 - Environmental protection activities [3,47].

5. Comprehensive production approach:
 - Pre-planting phase: Treatment of seed potatoes (40 kHz, 300 W, 15 min) stimulates germination and metabolism [17].
 - Processing process: Ultrasound improves frying parameters and sensory quality [14].
 - Final product: better texture, color and storage stability are achieved [14].
6. Directions of technology development:
 - Integration with membrane processes in the production of concentrates.
 - Use of high-pressure ultrasound for starch modification.
 - Development of continuous processing systems for industrial applications.
 - Automation and optimization of sonication parameters.
 - Research on the impact on the nutritional value of potato products.
7. Implementation of ultrasonic technology in the production of chips requires:
 - Standardization of processing parameters for different potato varieties.
 - Economic analysis of investment and operating costs.
 - Long-term studies of agrotechnical effects.

Ultrasonic technology is a promising innovation for the potato industry, offering revolutionary potential in terms of quality, economy and sustainable development. Its versatile application, from seed potato processing to optimization of processing processes and improvement of the quality of the final product, makes it a key area for further research and implementation.

4.10. Limitations of Ultrasound Technology

While ultrasound technology offers numerous advantages in food processing, it also has several limitations and challenges that need to be considered:

Limited Penetration Depth: Ultrasound waves, particularly high-frequency ones, have limited penetration depth in dense and complex food matrices like protein-rich foods. This can restrict its effectiveness to the surface layers of the food.

Inconsistent Treatment: Achieving uniform treatment throughout a large volume of food can be challenging. The intensity of ultrasound waves can attenuate as they travel through the medium, leading to uneven processing.

Food Matrix Dependency: The effectiveness of ultrasound varies significantly depending on the type and properties of the food matrix (e.g., viscosity, particle size, composition). Optimal parameters need to be determined for each specific food product.

Energy Consumption and Scalability: While often considered energy-efficient compared to traditional thermal methods, scaling up ultrasound technology for large-scale industrial applications can be energy-intensive and may require significant capital investment.

Microbial and Enzyme Resistance: Certain microorganisms, particularly bacterial spores, and some enzymes exhibit high resistance to ultrasound treatment alone. Combining ultrasound with other methods like heat (harmonization) or pressure (manosonication) is often necessary for effective inactivation.

Potential for Undesirable Effects: High-intensity ultrasound can potentially lead to undesirable changes in food quality, such as texture degradation, lipid oxidation (due to free radical production), and flavor alterations in some sensitive foods. Careful optimization of treatment parameters is crucial to avoid these effects.

Difficulty in Real-time Monitoring and Control: Monitoring and controlling the ultrasound treatment process in real-time within complex food systems can be challenging, making it difficult to ensure consistent and optimal results.

Cost of Equipment and Implementation: The initial investment cost for industrial-scale ultrasound equipment and the expertise required for its implementation and operation can be a barrier for some food processors.

Lack of Standardization: Standardized protocols and guidelines for ultrasound applications in various food processing areas are still under development, which can hinder its widespread adoption and regulatory approval.

Limited Understanding of Mechanisms: While the basic principles of ultrasound in food processing are understood, the precise mechanisms of its interaction with different food components and microorganisms are still being investigated. This can make it challenging to predict and optimize its effects.

Addressing these limitations through ongoing research and development is crucial for the broader and more effective application of ultrasound technology in the food industry.

5. Conclusions

Ultrasound technology has significant potential to optimize various stages of potato production, from seed potato growth stimulation, through improving processing parameters (e.g., frying and reducing discoloration), to increasing the quality and durability of the final product.

The implementation of ultrasonic technology in the potato industry is consistent with the idea of sustainable development, offering opportunities to reduce the use of chemical additives in processing and potentially plant protection products in cultivation, which can contribute to reducing the negative impact on the environment.

Potato varieties and chip quality:

Best: ‘Tajfun’ and ‘Syrena’ have very low reducing sugar content, minimizing the risk of browning and ensuring high quality.

Acceptable: ‘Vineta’ and ‘Satina’ (with borderline reducing sugar content) can be used with strict frying control.

Not recommended: ‘Denar’, ‘Lord’, ‘Owacja’ and ‘Zagłoba’ have too high reducing sugar content, which leads to excessive browning and poor taste.

Influence of climate: Dry and warm summers favor low reducing sugar content. Cool and humid summers increase their level, requiring selection or process modification.

Key quality factors: Color is strongly related to reducing sugar level (high levels cause browning). Fat content has little direct effect on other quality characteristics. Control of reducing sugars is a priority.

Ultrasound technology holds significant promise for the agri-food industry, particularly in potato processing. By optimizing various stages from seed potato growth to the final product, ultrasound can directly contribute to improving food quality, as evidenced by its potential to reduce undesirable browning in chips and enhance their sensory attributes. This is especially relevant given the critical role of controlling reducing sugar content, a key factor for chip quality, which ultrasound may help modulate.

The integration of ultrasound aligns with principles of sustainable development, offering a non-invasive method to potentially lessen reliance on chemical additives in processing and plant protection products in cultivation. This makes it a valuable tool for producers aiming to deliver high-quality, consistent food products while simultaneously reducing environmental impact.

The data underscores the importance of variety selection (e.g., ‘Tajfun’, ‘Syrena’) and the potential for ultrasound to mitigate challenges posed by less favorable varieties or climatic conditions, thereby enhancing the overall processing suitability of raw materials for a more predictable and premium final product.

Proposed further research: Analysis of the influence of other components on browning and development of predictive models combining agrotechnical data with processing parameters.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, P.P. and B.S.; methodology, P.B., P.P., B.S.; software, P.B.; validates P.B. and P.P.; formal analysis, P.B.; B.S.; investigation, P.P.; resources P.P., P.B.; data curation, P.P., B.S.; writing—original draft preparation, P.B., P.P.; writing—review and

editing, B.S., P.P.; visualization, P.B.; supervision, B.S.; project administration, P.P.; funding acquisition B.S. All authors have read and agreed to the published version of the manuscript.” Please turn to the [CRediT taxonomy](#) for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Abbreviations

US	Ultrasonic treatment/sonication
ROS	Reactive Oxygen Species
SOD	Superoxide Dismutase
CAT	Catalase
Genes related to carbohydrate metabolism:	
<i>InvInh2</i> (invertase inhibitor)	regulates sucrose breakdown
UGPase (UDP-glucose pyrophosphorylase)	key enzyme in starch synthesis
Amyl (amylase genes)	control starch degradation
PPO	Polyphenol Oxidase
NMR	Nuclear Magnetic Resonance
SEM	Scanning Electron Microscopy
MALDI-TOF	Matrix-Assisted Laser Desorption/Ionization Time-of-Flight

All terms are consistent with the nomenclature used in: IUPAC (International Union of Pure and Applied Chemistry), Food Chemistry (Elsevier), Journal of Agricultural and Food Chemistry.

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