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Toward Enhanced Seed Potato Yield: Ultrasonication Techniques for Sustainable Agricultural Development

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Abstract: The study aimed to explore the potential of ultrasonication techniques in seed potato production as a sustainable agricultural innovation. By improving seed potato efficiency and promoting resource optimization, this research aligns with the goals of sustainable agricultural and rural development, addressing challenges such as food security, environmental preservation, and economic viability in rural farming communities. The study was conducted over three years in the central–eastern region of Poland, utilizing a randomized block design with a split-split-plot approach. The main experimental factor was the cultivation technology, which included (a) an innovative ultrasonic pre-sowing treatment method and (b) a traditional cultivation method without such treatment. The secondary factor was the potato varieties. The ultrasonic treatment of tubers was performed using an ultrasonic tub-type device equipped with piezoelectric transducers. Cultivation technology, potato varieties, and weather conditions had a significant impact on the yield of tubers in the seed potato fraction size, the number of tubers in this fraction, and the multiplication coefficient. Additionally, the genetic characteristics of the studied varieties and random environmental factors significantly influenced the weight of a single seed potato tuber and the number of shoots produced by each plant.

Keywords: seed potato production; potato cultivation efficiency; environmental impact reduction; ultrasonication; sustainable seed treatment; advanced cultivation practices

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1. Introduction

Ultrasonic waves have the ability to induce physical and chemical changes in liquid media through the phenomenon of acoustic cavitation. The phenomenon of cavitation, especially acoustic, is used in many fields, such as industry (ultrasonic cleaning, emulsification, material processing), chemistry (synthesis, particle fragmentation), environmental protection (sewage treatment, removal of pollutants), food industry (sterilization, extraction of components), medicine (lithotripsy, biotechnology), and energy (biofuel production, sonochemical catalysis). Cavitation enables the intensification of processes and improvement of their efficiency in various industries. Additionally, recent research demonstrates the potential of ultrasonics in areas such as nanotechnology, biomedicine, the food industry, and pharmaceuticals. Ultrasonic techniques are also employed to improve the extraction processes of bioactive compounds from plants, accelerate chemical reactions, and enhance the efficiency of various technological processes. Therefore, there is a growing interest in research on the application of ultrasonics in a wide range of applications, contributing to the dynamic development of this field of science and technology [1,2].

All living organisms interact with sound waves in various ways. However, certain frequencies and intensities of sound can adversely affect human hearing and overall health. Sounds within the human audible range (20 Hz to 20 kHz) are of particular concern, as excessive exposure can lead to auditory and non-auditory health issues. Frequencies below 20 Hz, known as infrasound, and those above 20 kHz, called ultrasound, are beyond the range of human hearing but can still influence biological systems under specific conditions. Despite being inaudible, humans can harness these waves for selected applications. Ultrasound (US) finds wide-ranging applications across various fields, particularly in medical diagnostics (e.g., ultrasonography). Ultrasound is widely used in agriculture and in food technology and safety. In agriculture, it is used to monitor soil quality, fertilization, and in plant protection processes, e.g., in the detection of plant diseases or pests. In food technology, ultrasound is used to improve the extraction processes of bioactive ingredients, food preservation (e.g., elimination of bacteria), and emulsions, as well as in the analysis of the quality of food products. Thanks to its ability to precisely affect molecules, ultrasound contributes to improving the efficiency of production processes and also increases the safety and durability of food. Scanning devices collect these scattered or reflected sound waves to create images [1–3]. Additionally, ultrasound has applications in the chemical and processing industries, primarily due to acoustic cavitation. Acoustic cavitation is a process where sound waves interact with air bubbles in a liquid, leading to their formation, growth, and collapse. This process finds wide applications in material synthesis, food processing, and many other fields [1].

Ultrasonic technologies have diverse applications in fields such as medicine, agriculture, and food processing, mainly due to their ability to induce physical and chemical changes in liquid media via acoustic cavitation. These effects are used in areas like emulsification, extraction, and seed stimulation. For instance, in the UAE, ultrasonic-assisted extraction (UAE) combined with volatile natural deep eutectic solvents (VNADESs) has led to an eco-friendly process for extracting lycopene from tomato skins [1–6].

Was found [4] that physical factors like ultrasound can improve potato seed quality and increase yield, particularly during the early stages such as germination and seedling emergence. These techniques have shown promise in enhancing agricultural practices while reducing chemical usage, supporting the principles of integrated farming.

Ultrasound can improve nutrient uptake. By improving the permeability of cell membranes, ultrasound can facilitate the transport of water and minerals from the soil to plants, which promotes their better nutrition.

Ultrasound can also stimulate plant growth and development: Ultrasound can stimulate seed and tuber germination, root growth, and increase the number of shoots and leaves, which ultimately translates into higher yields. Ultrasound is a promising tool in sustainable agriculture, as ultrasonic technology is environmentally friendly and does not require the use of chemical growth stimulants or excessive fertilizers. It can reduce the pressure on natural resources by improving the efficiency of nutrient uptake, which allows for a reduction in the use of mineral fertilizers. In addition, this technology supports sustainable agriculture, as it is safe for soil, water, and ecosystems. Thanks to its stimulating properties, ultrasound can be a modern innovative solution in the pursuit of increasing agricultural productivity while reducing its impact on the environment [7–10].

The application of ultrasonic techniques in seed potato cultivation for sustainable agriculture can contribute to achieving effects such as the following:

- Improvement of seed potato quality: Ultrasound technology enhances the physiological traits of seed potatoes, such as size uniformity and health, making them more resistant to diseases and environmental stresses. This supports higher yields in sustainable systems.

- Enhanced germination capacity: Ultrasonics stimulate metabolic processes in potato tubers, increasing germination rates. This is critical for sustainable farming, where high-quality seed material reduces the need for chemical interventions.
- Reduction in chemical usage: Ultrasound serves as an alternative to traditional chemical treatments, improving seed potato health and quality while minimizing environmental impact, aligning with eco-friendly farming practices.
- Improved nutrient uptake efficiency: By modifying tuber surface properties, ultrasound enhances water and nutrient absorption. This leads to faster plant development and better resource utilization from the soil.
- Minimized production losses: ultrasonic treatments reduce losses caused by improper storage or seed diseases, ensuring stable production levels in farms adhering to sustainable agriculture principles.
- Energy efficiency: ultrasound techniques are energy-saving and require minimal labor, making them environmentally friendly and suitable for sustainable farming systems.
- Versatility and scalability: Ultrasonic technology can be integrated into various cultivation systems, making it adaptable for both small and large farms, supporting rural development and sustainable agricultural practices [6–12].

The integration of ultrasonic techniques in seed potato cultivation offers significant benefits for quality improvement, resource efficiency, and sustainability. These methods support environmentally friendly farming by reducing chemical use and production losses while increasing germination rates and nutrient absorption. Their scalability and adaptability further contribute to the development of sustainable agriculture systems.

The main limitation in potato yields is the lack of high-quality seed potatoes, especially for small and marginal farmers in Southern and Eastern Europe. Factors such as varietal purity, seed tuber health, physiological age, pests and diseases, changes in virus vector relationships, and insufficient knowledge of seed potato planting techniques significantly impact seed potato quality. Both pre- and post-harvest factors, including variety selection, seed potato production conditions, cultivation technology, tuber calibration, plant selection, plant protection measures, harvesting, and storage, are crucial for seed potato quality. This publication focuses on innovative factors like tuber sonication before planting to improve seed potato quality and increase seed yield, providing farmers with the highest-quality seed materials of potato [7,8]. In potato cultivation, the preparation of propagating material, including its enhancement, plays a crucial role before planting. Traditional methods of preparing seed material include the sorting and fractionation of tubers [7] and stimulating and treating tubers against pathogens [8–10]. The application of ultrasound technology (UT) by [10] increased chlorophyll content, photosynthesis, stomatal conductance, transpiration, antioxidant enzyme activity (superoxide dismutase, peroxidase, catalase), and soluble protein and sugars while reducing the level of malondialdehyde in sugarcane leaves. Their study showed that a more developed root system, more efficient photosynthesis, and better antioxidant properties after UT treatment (2–5 min, 20–40 kHz) contribute to the increased yield and quality of sugarcane, which confirms the potential of this technology in sustainable agricultural production. Such studies have not been conducted on potatoes yet, but a similar response of plants to UT can be expected.

Nowadays, chemical and physical treatments can be combined [5,6,11]. The aim of the study is to enhance the quality of the propagative material of several potato varieties through the application of ultrasound technology prior to planting [12,13]. Showed [13] that the piezoelectric ultrasound (PE-US) constitutes an acute abiotic stress that significantly alters the transcriptome and physiological traits of in vitro potato plantlets, but the plants demonstrate the ability to mitigate the stress over time (within 4 weeks) through enhanced antioxidant enzyme systems and functional metabolic adaptations, suggesting potential for PE-US as a tool to influence plant growth and stress responses. Thanks to these rather complex technologies, better growth and development of plants can be achieved, which can be observed even in subsequent generations [5,6,13]. The alternative research hypothesis posits that potato cultivation technology utilizing the ultrasonic treatment of tubers before planting will lead to an increase in the number of stems per plant, overall yield, seed potato yield, number of their tubers, individual seed tuber mass, and multiplication coefficient compared to the null hypothesis with traditional cultivation technology.

2. Materials and Methods

The research was conducted from 2015 to 2017 in Uhnin, located in East–Central Poland. The study area featured loamy soil derived from sandy clay, classified under the NRCS-USDA system [14].

2.1. Field Research

A field experiment was conducted using a randomized split-plot design, with three replications. The first-order factors were the technologies utilizing ultrasound as a pre-planting treatment. The second-order factor consisted of eight edible potato varieties from four earliness groups (‘Denar’ and ‘Lord’ varieties—very early; ‘Owacja’ and ‘Vineta’—early; ‘Satina’ and ‘Tajfun’—intermediate early; and ‘Syrena’ and ‘Zagłoba’—intermediate late). Ultrasound sonication of seed potato tubers was performed using a tank ultrasound device equipped with piezoelectric ultrasonic transducers.

The field experiment was conducted according to the methodology of cultivar economic value assessment (WGO) [15], applicable in Stations and Experimental Varieties Assessment Centers. Mineral fertilizers (potassium–phosphorus) were applied to the soil before planting, with the amount of mineral fertilization determined based on the soil’s nutrient content. The experiment utilized planting material classified as EU Class A. Fertilization was applied at consistent rates of 80 kg N, 35 kg P, 100 kg K, and 25 t·ha^{-1} of manure. Mineral fertilizers were incorporated into the soil using an aggregate consisting of a cultivator and a string roller. The tubers were then manually planted in the prepared field.

Potato tubers were planted manually each year during the last ten days of April, maintaining a spacing of 67.5 × 37 cm. The harvest area per plot measured 15 m^2. Plant protection measures against diseases, pests, and weeds were implemented following the guidelines and principles of Good Agricultural Practice (GAP) [16]. During the potato vegetation period, protection against early and late blight was applied, and Colorado potato beetle was controlled when detected using available preparations. Harvesting tubers was performed at the stage of full physiological maturity according to the 99-degree BBCH scale [17]. Throughout the growing season, plant care followed the principles of GAP, and protection against the Colorado potato beetle and potato blight was implemented using approved pesticides in accordance with the Institute of Plant Protection-National Research Institute guidelines. Harvesting was conducted between 24 August and 24 September depending on the technical maturity of the tubers and the earliness group of each cultivar.

The agricultural practices varied seasonally and year-to-year and included soil tillage, herbicide application, seed potato planting, mechanical weed control, and the use of fungicides and insecticides to manage crop health.

During the autumn seasons of 2014 to 2016, winter plowing was carried out to a depth of approximately 27 cm to prepare the soil. Herbicides were applied to forecrops for weed control, with the following products used each year:

- Autumn 2014: Lentipur Flo 500 SC (1 dm^3/ha), Snajper 600 SC (1 dm^3/ha), and Glean 75 WG (0.01 kg/ha).
- Autumn 2015: Bizon (1 dm^3/ha).
- Autumn 2016: Lentipur Flo 500 SC (1 dm^3/ha), Snajper 600 SC (1 dm^3/ha), and Glean 75 WG (0.01 kg/ha).

Spring 2015–2017: Spring activities focused on seed potato planting, weed control, fertilization, and pest management. The specific steps included soil preparation and planting involving harrowing, NPK fertilization, cultivation with an aggregate, manual planting of potato tubers, and earthing up. Weed control was carried out as part of the process. Mechanical weed control techniques were employed. Harvesting: potatoes were harvested using a potato elevator digger.

Fungicides: to manage fungal diseases, a combination of fungicides was applied at different dosages as follows:

- Infinito 867.5 SC (1.6 dm^3/ha^{-1}) was used across all three years. Ridomil Gold MZ 67.8 (2 kg ha^{-1}) was applied in spring 2015.
- Acrobat MZ 69 WG (2 kg ha^{-1}) was added to the fungicide regimen in spring 2016 and 2017.

Insecticides: to control insect pests, a variety of insecticides were utilized across the years, such as the following:

- Spring 2015: Apacz 50 WG (0.04 kg ha^{-1}) and Proteus CD (0.4 dm^3/ha^{-1}).
- Spring 2016: Actara 25 WG (0.08 kg ha^{-1}), Nuprid 200 SC (0.15 dm^3/ha^{-1}), and Apacz 50 WG (0.04 kg ha^{-1}).
- Spring 2017: Apacz 50 WG (0.04 kg/ha), Proteus CD (0.4 dm^3/ha), and Actara 25 WG (0.08 kg ha^{-1}).

This comprehensive approach ensured optimal conditions for the growth and health of the crops throughout the experiment.

Throughout the potato growth period, the stem count per plant was recorded for all potato plants within the plots.

At harvest, the total yield was determined, and samples were taken from beneath 10 potato plants to determine the yield structure according to fractions in accordance with Directive 2014/21/EU [18]. Based on these measurements, the proportion of seed potato mass in the total yield, the number of seed potatoes, and their average mass were determined. The seed potato yield was calculated using tubers with a diameter of 35–60 mm, excluding those severely damaged by pests or mechanical injury. The multiplication coefficient was determined by dividing the number of tubers in the 36–50 mm and 51–60 mm size fractions by the standard planting rate of 40,000 seed potatoes per hectare [18]. This coefficient essentially represents the ratio of the number of tubers produced within these size ranges to the number of seed potatoes planted per hectare. It indicates the potential multiplication or increase in the number of tubers during the growth cycle, providing insight into the efficiency of potato production and the yield obtained from the initial seed stock. Mathematically, it is expressed as

$$\text{Multiplication Coefficient} = \frac{\text{number of tubers of the fraction; 36–60 mm}}{\text{number of seed potatoes intended for 1 ha (40,000 pcs.)}} \tag{1}$$

2.2. Cultivation Technologies

In the field experiment, two cultivation technologies were employed as follows:

- Ultrasonic technology, where potato tubers were subjected to a sonication treatment before planting, involving the application of ultrasonic waves in a water environment at a temperature of 18 °C. Based on preliminary pilot studies, a sonication time of 10 min was adopted.

- Traditional technology, serving as the control group, involved soaking the tubers in distilled water to eliminate the influence of water on the physiology of potato tubers. The tubers were soaked in distilled water at a temperature of 18 °C for 10 min.

Construction and Operation of an Ultrasonic Device

The tuber seed material underwent immersion sonication using a bath-type ultrasonic device. The ultrasonic treatment of biological materials was carried out using an electronic UZM-type ultrasonic generator (Polsonic, Warsaw, Poland) paired with a transducer mounted at the bottom of the tank. The system had an acoustic power of 200 W, operating at a frequency of 50 kHz. To reduce noise pollution, the tank was covered during sonication. The process took place in an aqueous medium at a temperature of 18 °C for a duration of 10 min. Prior to ultrasound treatment, the sample, after being purified, was placed directly on the bottom of a container filled with an appropriate amount of water. The sonication device operated according to the manufacturer's instructions and in compliance with the CE declaration of conformity. Ultrasonic waves were generated by a piezoceramic transducer and transmitted through the water in the ultrasonic bath. These waves created alternating low-pressure waves at a frequency of 40,000 cycles per second. During the low-pressure phase, millions of vacuum bubbles formed, a process known as cavitation. As the pressure increased, the bubbles collapsed inward (imploded), releasing substantial energy that radiated outward, impacting all surfaces in the surrounding environment [19].

2.3. Characteristic of Potato Varieties

The tested potato varieties showed different characteristics in terms of tuber flesh color, culinary type, flavor, starch content, and harvest time. All varieties had yellow skin, and the color of their flesh ranged from light yellow (varieties: 'Denar', 'Lord' and 'Owacja') to yellow (varieties: 'Vineta', 'Satina', 'Tajfun', 'Syrena', and 'Zagłoba'). Culinary types were different, including 3 varieties classified as AB type ('Denar', 'Lord', and 'Vineta'), 3 varieties as B type ('Satina', 'Syrena', 'Zagłoba'), and 2 varieties as B-BC type ('Owacja' and 'Tajfun'). The taste assessment was homogeneous for almost all varieties except for the 'Satina' variety and was 7 on a 9-point scale, while 'Satina' had a better taste, at 0.5 points higher than the other varieties, which indicated good taste quality. Starch content ranged from 12.3% to 16.5%, with the highest values of this feature observed in varieties such as 'Tajfun' (16.5%) and 'Syrena' (15.4%), lower in 'Owacja' and 'Vineta' (13.5 and 13.7%, respectively), and the lowest in 'Denar', 'Lord', 'Zagłoba', and 'Satina' (12.3%, 12.4%, 12.6%, and 12.8%, respectively). Harvest dates varied depending on the maturity group, with very early varieties ('Denar', 'Lord') harvested in the first ten days of September, early varieties ('Owacja', 'Vineta') in the second ten days of September, medium-ripening varieties ('Satina', and 'Tajfun') in the third ten days of September, and medium–late varieties ('Syrena', and 'Zagłoba') in the first ten days of October. This diversity of features reflects the adaptability and potential culinary applications of the potato varieties studied [20].

2.4. Meteorological Conditions

Weather conditions during the study years are illustrated in Table 1.

Table 1. Rainfalls, air temperature, and the hydrothermal coefficient of Sielianinov during the growing season of potatoes (2015–2017).

Year	Month	Month Rainfall [mm]	% of the Long-Term Average *	Mean Air Temperature [°C]	Deviation from the Long-Term Norm [°C] *	Hydrothermal Coefficient of Sielianinov **
2015	April	61.8	171.7	8.8	0.9	2.3
	May	120.3	200.5	12.8	−0.9	3.0
	June	46.7	66.7	16.7	−0.1	0.9
	July	45.2	60.3	19.4	0.6	0.8
	August	6.1	8.7	21.4	3.7	0.1
	September	130.2	260.4	15.5	2.8	2.8
	Total	410.3				
2016	April	47.1	127.3	10.0	2.0	1.6
	May	46.3	78.5	15.3	1.5	1.0
	June	87.3	124.7	19.1	2.3	1.5
	July	114.1	152.1	20.5	1.6	1.8
	August	41.0	60.3	19.5	1.7	0.7
	September	11.8	23.1	15.5	2.6	0.3
	Total	347.6				
2017	April	51.8	140.0	8.1	0.1	2.1
	May	65.5	107.4	13.7	−0.1	1.5
	June	23.1	33.0	18.3	1.5	0.4
	July	132.0	176.0	19.4	0.5	2.2
	August	27.0	39.7	20.3	2.5	0.4
	September	83.3	163.3	14.8	1.9	1.9
	Total	382.7				

* The long-term average calculated for the period of 1971–2016 at the Uhnin meteorological station. ** The hydrothermal coefficient (k) was calculated using the following formula: $k = 10P \sum t$ [21], where P represents the total monthly precipitation in mm and Σt is the cumulative monthly air temperature above 0 °C. The index values were categorized as follows: extremely dry ($k \leq 0.4$), very dry ($0.4 < k \leq 0.7$), dry ($0.7 < k \leq 1.0$), moderately dry ($1.0 < k \leq 1.3$), optimal ($1.3 < k \leq 1.6$), moderately humid ($1.6 < k \leq 2.0$), wet ($2.0 < k \leq 2.5$), very humid ($2.5 \leq k \leq 3.0$), and extremely humid ($k > 3.0$).

Table 1 presents data on rainfall, air temperature, and the Sielianinov hydrothermal coefficient during the potato growing seasons from 2015 to 2017. The meteorological conditions varied across the study years. The Sielianinov hydrothermal coefficient, which assesses the effectiveness of precipitation and the formation of air temperatures for each month, was calculated for the potato growing period (April–September). The following is a summary of the findings:

2015:

- April: rainfall totaled 61.8 mm, which was 171.7% of the long-term average, with a mean air temperature of 8.8 °C, deviating 0.9 °C below the long-term norm.
- May: rainfall was 120.3 mm, representing 200.5% of the long-term average, accompanied by cooler temperatures.
- June: rainfall decreased to 46.7 mm, only 66.7% of the long-term average, with slightly cooler temperatures.

July and August had significantly reduced rainfall but warmer temperatures. September had high rainfall (130.2 mm), 260.4% of the long-term average, with a moderate temperature (Table 1).

In 2016, the rainfall varied throughout the months, with June being particularly dry (87.3 mm) at 124.7% of the long-term average, while July had significantly higher rainfall (114.1 mm) at 152.1%. August and September saw decreased rainfall compared to the previous months (Table 1).

In 2017, April and May had moderate rainfall and temperatures. June had minimal rainfall (23.1 mm), with a warmer temperature and a low hydrothermal coefficient. July had the highest rainfall (132.0 mm) and a slightly warmer temperature. August had lower rainfall but a warmer temperature compared to July. September had moderate rainfall and temperatures (Table 1).

The highest total rainfall over the three-year study period occurred in 2015; however, its distribution was not conducive to optimal tuber yield development. Conversely, 2016 had the lowest rainfall sum, but rainfall distribution favored tuber yield accumulation. The year 2017 showed variable meteorological conditions, with optimal water supply followed by very low water availability. Overall, the data demonstrate variations in rainfall and temperature across the growing seasons, highlighting the importance of understanding meteorological conditions for agricultural planning and management.

2.5. Soil Properties

The study was carried out on Luvisols, a soil type classified under the WRB system as one of the primary soil groups in the WRB for Soil Resources [22]. Luvisols are characterized by a clay-enriched horizon that undergoes significant seasonal shrinking and swelling due to changes in moisture content. These soils typically have a well-developed structure and are found in regions with temperate-to-subarctic climates. In the context of the experiment, the use of Luvisols as the soil type provides a suitable substrate for potato cultivation, offering adequate support for plant growth and development throughout the growing season. Additionally, the characteristics of Luvisols, such as their clay-rich nature and moderate pH, contribute to maintaining nutrient availability and promoting favorable conditions for plant establishment and yield. The characteristics of selected physicochemical soil features are presented in Table 2.

Table 2. Soil properties prior to the initiation of the experiment.

Year of Research	Content of Macronutrients [g kg^{-1} of soil]			Humus Content [g·kg^{-1}]	pH [KCL]
	P	K	Mg		
2015	89	109	78	0.94	5.9
2016	83	91	70	1.06	5.8
2017	106	98	63	1.03	6.6
Mean	93	99	70	1.02	-

Source: the analyses were carried out at the Central Research Laboratory of the University of Life Sciences in Lublin.

The soil on which the three-year study was conducted was characterized by high or very high levels of phosphorus and magnesium, while potassium ranged from low to medium levels. According to NRCS-USDA [14] standards, this soil was classified as sandy clay loam, with low organic matter content and slightly acidic pH (Table 2). Overall, the levels of macronutrients and soil humus content were relatively constant over the three years, with minor differences in soil pH. It was a soil with a balanced level of macroelements, suitable for the growth of potato plants.

2.6. Statistical Analysis

The research data were analyzed statistically using a three-factor analysis of variance (ANOVA) model in SAS 9.2 (2008) [23]. Following the ANOVA, the Newman–Keuls test was applied as a post hoc analysis to evaluate the significance of differences between the group means. This test allows for comparing all possible pairs of means and is known for its greater tendency to identify significant differences between groups, even when these differences are small, compared to the Tukey test. Additionally, a statistical analysis was conducted using descriptive statistics to better understand the characteristics of the data. Pearson's correlation coefficients were computed to assess the linear associations between variables. This coefficient quantifies both the strength and direction of the linear relationship between two continuous variables. It is a commonly used method for investigating relationships between variables in data [24].

3. Results

3.1. Number of Stems per Plant

The number of stems per potato plant can influence several aspects of its growth and productivity (Table 3).

Table 3. Number of stems per plant depending on technologies, variety, and years (2015–2017).

Cultivars	Technologies		Years			Mean
	Traditional	Ultrasound	2015	2016	2017	
'Denar'	4.75 a *	4.80 a	3.56 a	5.83 a	4.94 a	4.78 a
'Lord'	3.76 a	4.20 a	3.54 a	4.82 ab	3.60 b	3.98 c
'Owacja'	3.95 a	4.16 a	3.68 a	4.00 b	4.49 a	4.06 bc
'Vineta'	4.30 a	4.57 a	3.48 a	5.06 a	4.76 a	4.44 ab
'Satina'	4.70 a	4.90 a	4.08 a	5.33 a	4.99 a	4.80 a
'Tajfun'	3.98 a	4.06 a	3.20 ab	4.72 ab	4.13 a	4.02 bc
'Syrena'	4.62 a	4.38 a	4.06 a	4.77 ab	4.67 a	4.50 ab
'Zagłoba'	3.50 a	3.37 a	2.89 b	4.21 b	3.21 b	3.44 d
Mean	4.19 b	4.31 a	3.56 c	4.84 a	4.35 b	4.25

* The letter symbols assigned to the means (significance groups) represent homogeneous (statistically equivalent) groups. If two or more means share the same letter, it indicates no statistically significant difference between them. The subsequent letters, such as a, b, c, etc., correspond to groups ranked in descending order.

The influence of stem count on this parameter varied depending on cultivation conditions, potato varieties, and other environmental and agronomic factors (Table 3).

The results show that stem count per plant depends on cultivation technology, potato variety, and years. The use of ultrasound before planting as a technology significantly increased the stem count per plant compared to traditional technology (Table 3). In most varieties, the stem count per plant was slightly higher when ultrasound was used, although this was not statistically confirmed. This suggests a certain positive effect of this technology on plant growth. Significant differences were also observed in the stem count per plant among the tested potato varieties. Varieties such as 'Satina' and 'Denar' produced the highest number of stems per plant. In the next homogeneous group of varieties were 'Vineta' and 'Syrena', followed by 'Owacja' and 'Tajfun', with the lowest number of stems being observed in the 'Zagłoba' variety, which showed a tendency to have a higher stem count per plant compared to other varieties in the study sample (Table 3).

Changes in stem count per plant were observed in subsequent years. In 2016, a year favorable in terms of thermal and precipitation conditions, the highest number of stems per plant was obtained, while in other years, it was lower, and in the dry year of 2015, it was the lowest. This could be the result of different weather conditions and other environmental factors affecting plant growth in the study years (Table 3).

The response of the tested varieties to climatic and soil conditions was also varied. In the dry year of 2015, the highest number of stems was produced by the 'Vineta' variety, but homogeneous in terms of this feature were also the varieties 'Satina', 'Vineta', 'Owacja', 'Lord', and 'Denar'. Similarly to 'Lord' and 'Syrena', the lowest number of stems in the same year was produced by the 'Zagłoba' and 'Tajfun' varieties. In 2016, the highest number of stems per plant was distinguished by the following varieties: 'Denar', 'Satina', and

Vineta. The next homogeneous group consisted of the following varieties: 'Lord', 'Syrena', and 'Tajfun', and the last group consisted of 'Zagłoba' and 'Owacja'. In 2017, the group of varieties with the lowest stem count per plant included the 'Lord' and 'Zagłoba' varieties, while the remaining varieties were in one homogeneous group with a greater potential for stem formation (Table 3).

The research also indicates that a significant response of potato plants to cultivation technology using ultrasound was noted in 2015 and 2017 under unfavorable thermal and precipitation conditions (Figure 1). The research also indicates that a significant response of potato plants to cultivation technology using ultrasound was noted in 2015 and 2017 under unfavorable thermal and precipitation conditions (Figure 1).

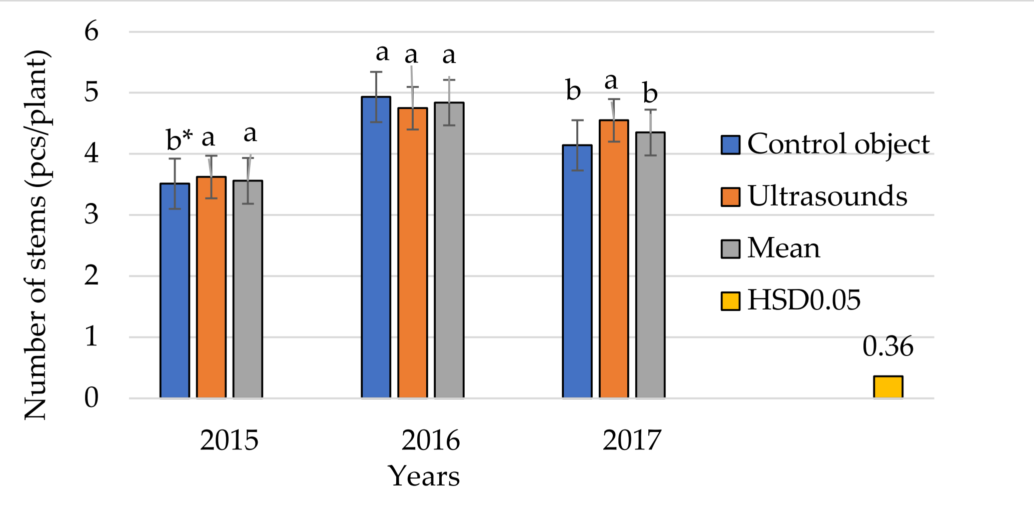

Figure 1. Effect of cultivation practices and duration on stem count per plant. * The existence of identical letter indices in the means (at a minimum) indicates a lack of statistically significant differences among them. The subsequent letter indices (a, b) delineate the groups in descending order.

These conclusions can help potato producers better understand the impact of various factors on plant growth and development, which can be useful in planning crops and selecting appropriate varieties and technologies. Generally speaking, a greater number of stems can contribute to increased productivity, provided proper cultivation management and the availability of adequate resources for the plants.

3.2. Yield of Seed Potatoes

The average potato seed potato yield in the experiment was impressive, reaching 37.95 t ha^{-1} (Table 4). Pre-planting ultrasound treatment proved highly effective, boosting potato seed yield per unit area by approximately 7% compared to cultivation methods that did not include this treatment. Genetic factors significantly differentiated the tested varieties. The most productive variety was 'Syrena', but within the same homogeneous group, varieties such as 'Denar', 'Satina', and 'Zagłoba' also stood out. In the second homogeneous group, varieties like 'Lord' and 'Tajfun' were found, and in the least productive group, there were varieties like 'Vineta' and 'Owacja' (Table 4).

Fluctuating meteorological conditions throughout the study years had a substantial influence on potato seedling yield. The average yield in 2015 was notably lower than in other years, indicating that both atmospheric and soil conditions during that year were unfavorable for potato production. In contrast, the highest yield of this tuber fraction was recorded in 2016, when weather conditions were most conducive to potato growth.

Meanwhile, the 2017 yield, while significantly higher than the drought-affected 2015, was still lower than 2016, reflecting the optimal water availability during the potato growing season that year. The tested potato varieties showed a varied response to soil and climatic conditions during the study years. It was in 2017, with unusual weather patterns, that the tested varieties showed significantly different yields. In the group of varieties with the highest yields of potato seedlings were 'Denar', 'Lord', 'Satina', and 'Syrena'. In the next group, with homogeneous yields, were varieties like 'Vineta', 'Tajfun', and 'Zagłoba', while the variety with the lowest yield of potato seedlings was 'Owacja'. The tested potato varieties responded similarly to cultivation technologies. There was also no interaction observed between cultivation technologies and the study years (Table 4).

Table 4. Impact of cultivation technologies, potato varieties, and growing seasons on seed potato yield (t ha^{-1}).

Cultivars	Technologies		Years			Mean
	Traditional	Ultrasound	2015	2016	2017	
'Denar'	40.25 a *	40.19 a	27.06 a	48.76 a	44.84 a	40.22 a
'Lord'	34.93 a	39.80 a	28.06 a	44.98 a	39.07 a	37.37 ab
'Owacja'	34.22 a	36.00 a	30.09 a	41.31 a	33.93 b	35.11 b
'Vineta'	33.75 a	35.76 a	26.01 a	41.20 a	37.04 ab	34.75 b
'Satina'	37.01 a	42.77 a	35.33 a	42.78 a	41.56 a	39.89 a
'Tajfun'	36.90 a	37.87 a	27.20 a	47.51 a	37.44 ab	37.39 ab
'Syrena'	39.60 a	42.24 a	34.80 a	46.56 a	41.40 a	40.90 a
'Zagłoba'	37.04 a	38.96 a	31.78 a	46.21 a	36.00 ab	38.00 a
Mean	36.71 b	39.20 a	30.04 c	44.91 a	38.91 b	37.95

* The designations are as in Table 3.

3.3. Proportion of Seed Potatoes in the Total Yield

The average share of seed potato in the total tuber yield was 90.9% (Table 5). The implemented technologies did not significantly affect this parameter. The primary factors influencing the percentage of seed potato in the main yield were the weather conditions during the study years and the specific traits of the tested potato varieties. The 'Tajfun' variety exhibited the highest proportion of seedlings in the main yield, while the lowest was observed in the 'Zagłoba' variety. The remaining varieties were grouped into two homogeneous groups, namely 'Denar', 'Satina', and 'Syrena' and 'Lord', 'Owacja', and 'Vineta'.

Table 5. The impact of cultivation methods, potato varieties, and growing seasons on the proportion of seed potatoes in the overall yield.

Cultivars	Technologies		Years			Mean
	Traditional	Ultrasound	2015	2016	2017	
'Denar'	93.0 a *	92.8 a	94.3 a	89.9 a	94.6 a	92.9 ab
'Lord'	89.4 a	92.5 a	94.7 a	89.7 a	88.4 b	90.9 b
'Owacja'	92.4 a	90.5 a	95.2 a	87.8 a	91.4 a	91.5 b
'Vineta'	90.5 a	89.4 b	94.7 a	86.0 b	89.1 a	89.9 b
'Satina'	91.2 a	94.2 a	96.0 a	89.0 a	92.1 a	92.7 ab
'Tajfun'	94.5 a	95.2 a	94.6 a	94.5 a	95.6 a	94.9 a
'Syrena'	91.9 a	92.8 a	95.1 a	89.8 a	92.1 a	92.3 ab
'Zagłoba'	81.3 b	83.2 b	93.4 a	77.0 b	76.3 b	82.2 c
Mean	90.5 a	91.3 a	94.7 a	88.0 c	90.1 b	90.9

* The designations are as in Table 3.

The highest proportion of seedlings in the main yield was recorded in 2015, while the lowest was in 2016 (Table 5). In that year, the interaction of meteorological conditions with the characteristics of the tested varieties was observed.

These varieties were divided into two homogeneous groups. The varieties with a higher proportion of seedlings included ‘Denar’, ‘Lord’, ‘Owacja’, ‘Satina’, ‘Tajfun’, and ‘Syrena’, while those with a lower proportion of tubers in this fraction included the varieties ‘Vineta’ and ‘Zagłoba’. The interaction of the characteristics of the tested varieties with the meteorological conditions during the potato growing period was observed. In the second year of the study (2016), the variety ‘Tajfun’ had the highest yield, but homogeneous in terms of this characteristic were the varieties ‘Denar’, ‘Lord’, ‘Owacja’, ‘Satina’, and ‘Syrena’. The variety ‘Zagłoba’ had the lowest proportion of seed potatoes, while ‘Vineta’ exhibited consistency in this regard. In 2017, the varieties ‘Lord’ and ‘Syrena’ showed the smallest share of tubers in the seed potato fraction, and both were classified into the same homogeneous group. The variety ‘Tajfun’ had the highest proportion of seed potato in the yield, while the other varieties were classified into the same homogeneous group (Table 5).

3.4. Number of Seed Potatoes

The number of seed potatoes mainly determines the quantity of plants that will be planted on a given cultivation area. The greater the number of seed potatoes, the more plants will be grown, which can affect the final yield. In agricultural practice, the decision regarding the number of seed potatoes is crucial for the optimal utilization of the available area and achieving the desired yield (Table 6). The analysis of the results in Table 6 shows that both technology and potato varieties, as well as the years of cultivation, have an influence on the number of potato tubers (in thousand pcs per hectare).

Table 6. The impact of cultivation technologies, potato varieties, and years on the number of seed potatoes (thousand pieces per hectare).

Varieties	Technologies		Years			Mean
	Traditional	Ultrasound	2015	2016	2017	
‘Denar’	324.1 a *	336.3 a	266.9 a	332.7 a	391.1 a	330.2 a
‘Lord’	280.0 a	318.7 ab	261.8 a	314.7 a	321.6 ab	299.3 b
‘Owacja’	291.6 a	314.1 ab	300.3 a	302.4 a	305.8 b	302.9 b
‘Vineta’	296.9 a	297.6 b	267.8 a	295.3 a	328.7 abc	297.3 b
‘Satina’	315.3 a	384.9 a	321.8 a	323.3 a	405.1 a	350.1 a
‘Tajfun’	302.1 a	333.3 a	269.1 a	331.1 a	352.9 a	317.7 ab
‘Syrena’	296.4 a	316.9 ab	293.3 a	290.9 a	335.8 abc	306.7 b
‘Zagłoba’	295.0 a	311.1 ab	287.8 a	337.6 a	283.8 b	303.0 b
Mean	300.2 b	326.6 a	283.6 c	316.0 b	340.6 a	313.4

* The designations are as in Table 3.

The use of ultrasound technology before planting had a significant impact on the number of seed potatoes compared to the traditional technology without this procedure, resulting in an increase in the number of seed potatoes by 8.9% or approximately 27,000 pcs, allowing for the additional planting of nearly 1 hectare of plantation area (Table 6). Considerable variation in the number of seed potatoes was noted among the different potato varieties. The ‘Satina’ and ‘Denar’ varieties exhibited the highest tendency to produce well-calibrated seed potatoes compared to the other varieties in the study.

Variations in the number of seed potatoes per hectare were recorded throughout the study years. The highest number of seed potatoes was observed in 2017, a year marked by fluctuating thermal and moisture conditions, whereas the lowest count occurred in the drought-affected year of 2015. This could be the result of atmospheric conditions, as well as other environmental factors affecting seedling production (Table 6).

The interaction of varieties with cultivation technologies was also demonstrated. In most cases, the use of ultrasound led to an increase in the number of seed potatoes per hectare, suggesting a positive impact of this technology on seed potato production. The varieties 'Satina', 'Tajfun', and 'Denar' showed the strongest reaction to the pre-planting ultrasound treatment on potato tubers, while the 'Lord', 'Owacja', 'Syrena', and 'Zagłoba' varieties were in the next homogeneous group and the 'Vineta' variety showed the weakest reaction (Table 6).

The response of potato plants to cultivation technologies was also influenced by vegetative conditions (Figure 2).

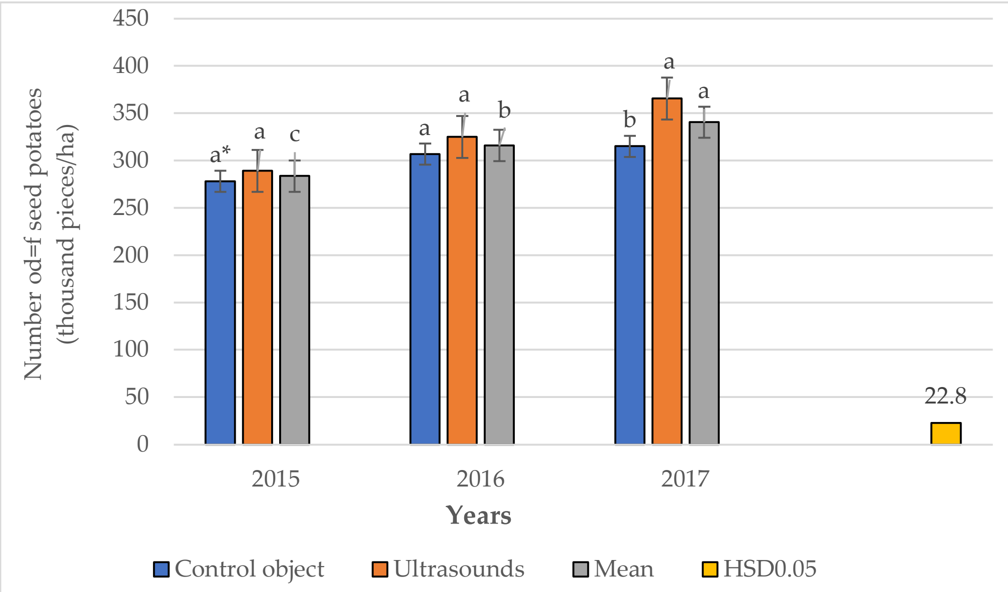

Figure 2. The influence of technologies and years on the number of seed potatoes. * The designations are as in Figure 1.

In 2017, during an atypical weather pattern, a significant increase in the number of seed potatoes was observed as a result of tuber sonication prior to planting. In the other study years, this technique demonstrated only a trend toward increasing the number of seed potatoes compared to the control technology (Figure 2). The selection of suitable cultivation technology and potato variety plays a crucial role in determining the quantity of seed potatoes, which directly impacts the potential potato yield. Potato producers are advised to consider these factors when making decisions about cultivation to optimize production and achieve desired yield outcomes.

3.5. Average Mass of a Seed Potato

The average weight of seed potatoes can significantly influence both their yield and the multiplication rate of potatoes. A higher average mass of seed potatoes typically leads to a greater number of tubers produced from a single seed potato. This means that plants will have the potential to produce a greater quantity of tubers, which in turn can contribute to an increase in the overall potato yield per hectare (Table 7).

The data presented in Table 7 indicate significant variations in the mass of individual seed potatoes depending on the factors analyzed. While the use of ultrasound prior to planting did not significantly affect this trait, certain varieties, such as 'Lord' and 'Vineta', exhibited a tendency toward an increase in individual seed potato mass when exposed to this technology. However, the genetic traits of the tested potato varieties significantly differentiated the value of this characteristic. The 'Syrena' variety exhibited a significantly higher average mass of seedlings compared to other varieties. The remaining varieties can be classified into two homogeneous groups, namely (a) 'Denar', 'Lord', and 'Zagłoba' and (b) 'Owacja', 'Vineta', 'Satina', and 'Tajfun' (Table 7).

Soil and climatic conditions had a notable influence on the average mass of individual seed potatoes. In 2016, the average seed tuber mass was significantly higher compared to 2015 and 2017, likely due to differences in environmental and weather conditions during those years.

Table 7. The impact of cultivation technologies, potato varieties, and growing seasons on the weight of seed tubers (g).

Varieties	Technologies		Years			Mean
	Traditional	Ultrasound	2015	2016	2017	
'Denar'	122 ab *	119 a	101 a	147 a	115 a	121 b
'Lord'	123 a	125 a	107 a	144 a	122 a	124 b
'Owacja'	117 ab	114 b	100 a	136 ab	111 a	116 bc
'Vineta'	113 b	119 a	96 a	139 ab	112 a	116 bc
'Satina'	118 ab	112 b	109 a	133 b	103 a	115 bc
'Tajfun'	121 ab	113 b	101 a	144 a	106 a	117 bc
'Syrena'	136 a	134 a	118 a	163 a	124 a	135 a
'Zagłoba'	126 a	124 a	110 a	138 ab	128 a	125 b
Mean	122 a	120 a	105 c	143 a	115 b	121

* The designations are as in Table 3.

The average mass of individual seed potatoes was also affected by the interaction between cultivation technologies and the specific growing seasons. In 2017, the technology showed a particularly beneficial effect, as the atypical weather conditions during the vegetation period triggered a defensive response in the potatoes. This led to the production of larger tubers, enabling the plants to better withstand drought and maintain their reproductive potential for the next cycle (Figure 3).

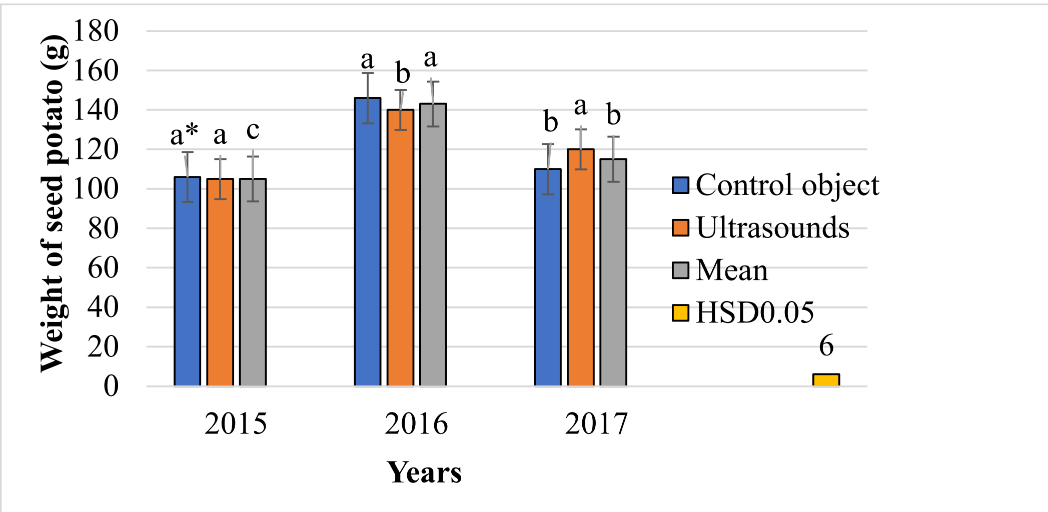

Figure 3. The impact of cultivation methods and growing seasons on the weight of individual seed potatoes. * The designations are as in Figure 1.

Therefore, the use of ultrasound technology may potentially increase the mass of seed potatoes, which can be beneficial for achieving higher potato yields. The choice of suitable potato varieties also significantly influences the mass of seed potatoes. Potato producers are advised to consider these factors when making decisions regarding cultivation in order to achieve optimal results in potato seed production.

Potato producers are advised to consider these factors when making decisions regarding cultivation in order to achieve optimal results in potato seed production. Incorporating ultrasound technology, selecting appropriate varieties, and staying informed about the latest research can lead to more efficient and productive potato farming practices.

3.6. Multiplication Coefficient

The potato multiplication coefficient is expressed as the ratio of the total mass of the potato yield to the mass of the seed potatoes used, and it serves as a key metric for assessing the efficiency of potato tuber production. This coefficient provides valuable insights into the productivity and effectiveness of different cultivation techniques and seed potato quality. The research results, which detail these findings, are presented in Table 8.

Table 8. The effect of cultivation technologies, potato varieties, and growing seasons on the multiplication rate of seed tubers.

Varieties	Technologies		Years			Mean
	Traditional	Ultrasound	2015	2016	2017	
'Denar'	8.1 a *	8.4 ab	6.7 a	8.3 a	9.8 a	8.3 ab
'Lord'	7.0 b	7.9 b	6.5 a	7.9 a	8.0 a	7.5 b
'Owacja'	7.3 a	7.8 b	7.5 a	7.6 a	7.6 b	7.6 b
'Vineta'	7.4 a	7.4 c	6.7 a	7.4 a	8.2 a	7.4 b
'Satina'	7.9 a	9.6 a	8.0 a	8.1 a	10.1 a	8.8 a
'Tajfun'	7.6 a	8.3 ab	6.7 a	8.3 a	8.8 a	7.9 ba
'Syrena'	7.4 a	7.9 b	7.3 a	7.3 a	8.4 a	7.7 b
'Zagłoba'	7.4 a	7.8 b	7.2 a	8.4 a	7.0 b	7.6 b
Mean	7.5 b	8.2 a	7.1 c	7.9 b	8.5 a	7.8

* The designations are as in Table 3.

The average value of the multiplication coefficient in the experiment was 7.8. The application of tuber sonification before planting contributed to a significant increase in this coefficient compared to traditional technology without ultrasonic treatment, from 7.5 to 8.2. The genetic properties of the examined varieties significantly influenced the magnitude of this parameter. The variety 'Satina' stood out with the highest value of this coefficient. The other varieties could be grouped into two homogeneous groups, with 'Denar' and 'Tajfun' belonging to the first group, and 'Syrena', 'Owacja', 'Zagłoba', 'Lord', and 'Vineta' to the second group (Table 8).

Climatic and environmental factors had a substantial influence on this parameter of potato seed quality. The highest value was recorded in 2017, a year marked by atypical weather patterns, including excessive rainfall in April and May, followed by a rainfall deficit during the critical period of tuber development. The lowest value of the multiplication coefficient was obtained in 2015 during a dry and very dry period from June to September (Table 8).

The response of the examined varieties to technologies using ultrasonic treatment on tubers before planting varied. The variety 'Satina' showed the greatest response to this technology, while the variety 'Vineta' showed no reaction to the applied ultrasonic treatment on tubers before planting. The remaining varieties were grouped into two homogeneous groups (Table 8).

The varying meteorological and soil conditions during the study years had diverse effects on the reproductive potential of the analyzed potato varieties. Only in 2017 was a significant increase in the multiplication coefficient observed under the influence of technology using ultrasonic treatment. In the remaining years, a positive trend toward increasing the value of this coefficient in technology using ultrasonic treatment was observed (Figure 4).

Recent advancements in plant physiology research suggest that ultrasound technology can enhance nutrient uptake, improve root development, and increase the stress resistance of plants. These benefits are particularly pronounced under suboptimal growing conditions, which may explain the significant increase observed in 2017, a year characterized by unfavorable weather conditions. Additionally, the ultrasonic treatment has been found to stimulate cellular activities that contribute to better growth and yield outcomes (Figure 4).

Moreover, recent studies have indicated that ultrasound can promote the expression of genes associated with growth and stress tolerance in plants, potentially leading to more robust and productive crops. This effect is dependent on the specific conditions of the growing environment, which could account for the variability in the results across different years.

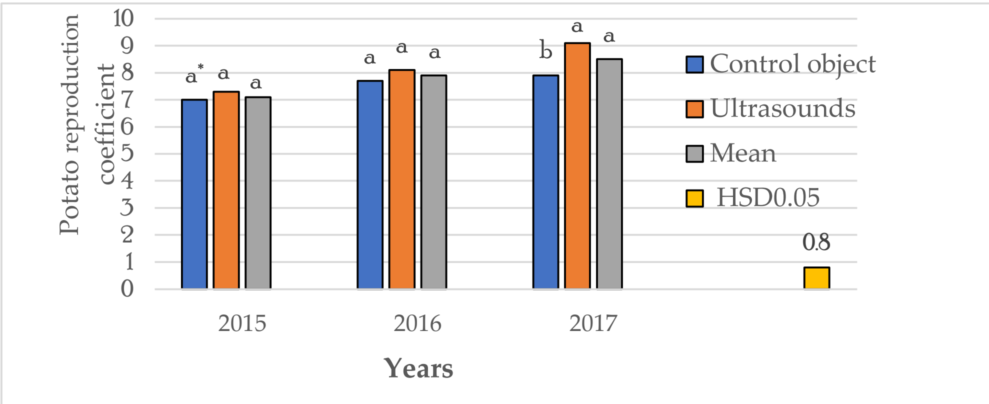

Figure 4. The effect of cultivation methods and growing seasons on the potato multiplication coefficient. * The designations are as in Figure 1.

The consistent positive trend observed in the other years aligns with the growing body of evidence supporting the benefits of ultrasonic treatment in agriculture. As technology advances, optimizing the parameters for ultrasound applications—such as frequency, duration, and timing—could further enhance its effectiveness.

In conclusion, integrating ultrasonic treatment into potato cultivation practices, combined with the careful consideration of meteorological and soil conditions, can lead to improved reproductive capabilities and higher yields. Continuous research and field trials are essential to fully harness the potential of this innovative technology.

The potato multiplication coefficient is the ratio of the total mass of potato tuber yield to the mass of seed potatoes used for their cultivation. If the average mass of the seed potato is higher, it means that each seed potato can produce a greater number of tubers during harvesting. As a result, the potato multiplication coefficient may be lower because despite a greater number of tubers, the total yield mass may not be significantly higher compared to the mass of seed potatoes used for cultivation. Therefore, although a higher average mass of seed potatoes may lead to a greater number of tubers and potentially increase the total potato yield, it may also affect reducing the multiplication coefficient. Hence, it is important to find a balance between yield and the multiplication coefficient to achieve optimal results in potato cultivation.

3.7. Descriptive Statistics of Potato Traits

The descriptive statistical analysis offers valuable insights into potato yield and quality parameters, including metrics such as the mean, median, standard deviation, range, minimum, maximum, and coefficient of variation, as well as distribution characteristics like skewness and kurtosis for each evaluated trait (Table 9).

Table 9. Summary statistics for the dependent variable (y) and the independent variables (x).

Specifications	y	x1	x2	x3	x4	x5
Mean	37.95	4.25	90.92	313.39	121.03	7.83
Median	39.60	4.26	92.45	310.00	118.00	7.75
Standard deviation	8.46	0.87	5.97	52.86	19.99	1.32
Kurtosis	−0.74	0.54	1.91	0.46	1.43	0.46
Skewness	−0.34	−0.16	−1.41	0.44	0.84	0.44
Range	37.13	5.64	29.32	296.00	129.00	7.40
Minimum	17.93	1.03	68.86	194.67	78.00	4.87
Maximum	55.07	6.67	98.18	490.67	207.00	12.27
Coefficient of variations (%)	22.30	20.40	6.56	16.87	16.52	16.87

y—seed potato yield ($t \cdot ha^{-1}$); x1—number of stems (pcs/plant); x2—share of seed potatoes (%); x3—number of seed potatoes (thousands of $pcs \cdot ha^{-1}$); x4—weight of medium seed potato (g); x5—reproduction coefficient.

The average seed potato yield (y) was 37.95 $t \cdot ha^{-1}$, exhibiting moderate variability. The distribution is slightly left-skewed, indicating that higher yields are somewhat more frequent. The median yield is marginally higher than the mean, reinforcing the left-skewed nature of the distribution. The standard deviation further reflects the spread of the yield data (8.46). A moderate variation in yield is observed, with yields generally falling within a range of 8.46 $t \cdot ha^{-1}$ around the mean. Skewness (−0.34): a small negative skew indicates a slight tendency for yields to be concentrated toward the higher end of the range. Kurtosis was negative, indicating a flatter distribution. The coefficient of variation (V) was 22.30% and means indicated moderate variability (Table 9).

The average number of stems (x1) per potato plant was 4.25. The median value was close to the mean, suggesting a symmetric distribution of data around the mean. The range of results for this parameter was 5.64, indicating that data ranged from 1.03 to 6.67 stems per plant. Kurtosis quantifies the extent to which the tails of a distribution are heavier and how far the data points deviate from the expected value. For the number of stems (x1), the kurtosis value of 0.54 suggests a leptokurtic distribution, meaning the tails are thicker than those of a normal distribution. Skewness, on the other hand, assesses the asymmetry of the data distribution. For the number of stems (x1), the skewness was −0.16, suggesting slightly longer tails on the left side of the distribution. The coefficient of variation (CV), which is the ratio of the standard deviation to the mean, expressed as a percentage, serves as an indicator of the relative variability within the data. The CV was 20.40%, indicating moderate variability (Table 9).

Proportion of seed potatoes (x2): The average proportion of seed potatoes is 90.92%. A strong negative skew suggests most values are closer to the upper limit, with fewer smaller values. Higher kurtosis suggested a greater concentration of data around the mean with more extreme values, while negative skewness indicated asymmetry toward higher values. Kurtosis and skewness were close to zero, suggesting a nearly normal distribution with limited variability. A leptokurtic distribution was shown, meaning the data have heavier tails and a sharper peak around the mean. Very low relative variability indicated a stable share of seed potatoes (Table 9).

The average number of seed potatoes per hectare (x3) was 313.39 thousand pieces. The standard deviation (52.86) showed moderate variability in planting density. Skewness (0.44) demonstrated a slight positive skew, meaning more values lay below the mean than above. The coefficient of variation (16.87%) indicated a moderate level of variability (Table 9).

The average weight of a seed potato (x4) was 121.03 g. Kurtosis and skewness were close to zero, indicating a nearly normal distribution with limited variability. The average reproduction coefficient (x6) was 7.83 (Table 9).

Reproduction coefficient (x5): On average, the reproduction coefficient is 7.83. The standard deviation (1.32) demonstrated low variability in the reproduction coefficient. Skewness (0.44) showed a slight positive skew, indicating most values were below the mean with a few larger values. For the range (7.40), variation spanned from 4.87 to 12.27, suggesting different levels of reproductive success. The coefficient of variation (16.87%) indicated a moderate level of variability (Table 9).

Independent variables: Most variables (except x2) exhibit moderate variability (coefficient of variation around 16–20%). Skewness varies, with x2 being strongly negatively skewed (high values dominate), while x4 and x5 are slightly positively skewed. These statistics suggest that seed potato yield (y) is influenced by various moderately variable independent factors. The strong skewness of x2 and the relatively consistent nature of x1 and x5 could imply that planting density (x3) and seed potato weight (x4) play crucial roles in explaining yield variability. In summary, the descriptive statistics analysis indicates variability in several parameters, possibly due to differences in cultivation conditions, the phenotypic variability of potato varieties, or agronomic practices (Table 9). Additionally, the symmetry of the data distribution around the mean suggests a uniform distribution of values in some cases, while shifts in the median value may indicate skewness in data distribution in some instances.

3.8. Relationships Between the Number of Stems, Tuber Yield, and Potato Seed Parameters

The correlation relationships between total yield, seed potatoes, and other quality parameters of seed potatoes are illustrated in Figure 5. Pearson's correlation coefficient analysis reveals that the closer the coefficient is to 1 or −1, the stronger the linear relationship between the two variables. Positive correlation coefficients (near 1) indicate a direct relationship, where an increase in one variable leads to an increase in the other. In contrast, negative correlation coefficients (near −1) suggest an inverse relationship, where an increase in one variable corresponds to a decrease in the other. Values close to 0 indicate a lack of linear relationship between variables.

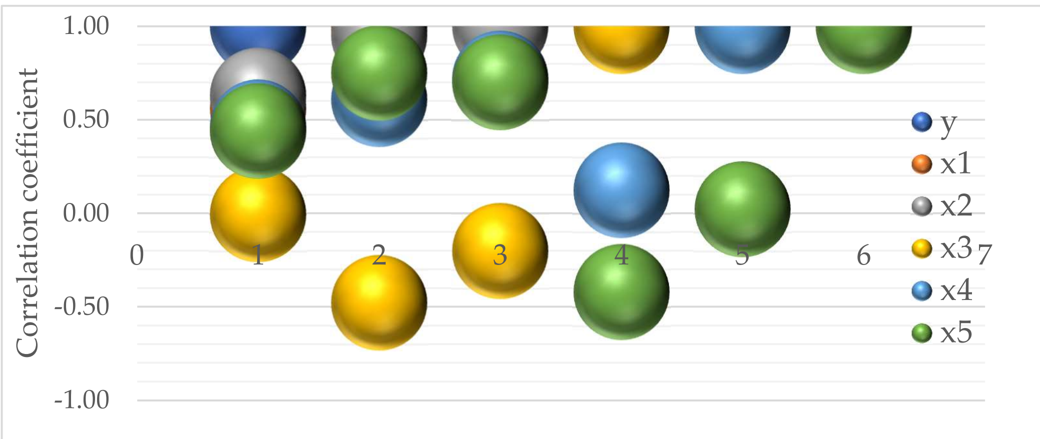

Figure 5. Pearson's correlation coefficients for seed potato yield and the parameters used to evaluate it. Y—seed potato yield (t·ha^{-1}); x1—number of stems (pcs/plant); x2—share of seed potatoes (%); x3—number of seed potatoes (thousands pcs/ha); x4—weight of an average seed potato (g); x5—reproduction coefficient.

Based on the data in Figure 5 the following conclusions can be drawn: the matrix presents Pearson's correlation coefficients between seed potato yield (y) and various cultivation factors (x1) through (x5).

Seed potato yield (y) and number of stems (x) (r = 0.63) points to a moderate positive correlation.

- y and x2 (share of seed potatoes) (r = −0.20) showed a weak negative correlation.
- y and x3 (number of seed potatoes) (r = 0.72) points to a strong positive correlation.
- y and x4 (mass of medium seed potato) r = 0.70 showed a strong positive correlation.
- y and x5 (multiplication coefficient) r = 0.72 points to a strong positive correlation (Figure 5).

Key relationships among factors: x3 (number of seed potatoes) and x5 (multiplication coefficient) r = 1.00 showed a perfect positive correlation. The weight of medium seed potato (x4) and share of seed potatoes (x2) r = −0.42 points to a moderate negative correlation.

Key insights: The number (x3) and weight of an average seed potato (x4) of seed potatoes strongly influence yield (y). The multiplication coefficient (x5) depends directly on the number of seed potatoes (x3).

The number of stems (x1) has a moderate positive correlation with the yield of seed potatoes (y), the number of seed potatoes (x3), and the weight of an average seed potato (x4). The share of seed potatoes (x2) shows weaker associations with other parameters.

The number of stems (x1) has been found to be associated with other characteristics of seed potato yield, such as the following:

- Number of seed potatoes: increasing the number of stems can lead to a higher production of seed potatoes, since each stem has the potential to generate more seed potatoes.
- Weight of an average seed potato: when a plant produces more stems, it may result in an increased total mass of seed potatoes, as a greater number of stems can mean a higher combined mass of tubers produced.
- Potato multiplication ratio: This ratio represents the total mass of harvested potato tubers to the mass of seed potatoes used for cultivation. An increase in the number of stems can potentially affect this ratio, as a higher number of stems may indicate a greater combined mass of harvested tubers, which could lead to a reduction in the multiplication ratio if the mass of the harvested potato yield does not increase proportionally to the mass of the seed potatoes.

The correlation coefficient value between the percentage share of seed potatoes (x2) and the number of seed potatoes (x3) was only r = 0.12. This means that there is a small positive correlation between the percentage share of seed potatoes and the number of seed potatoes. However, this relationship is not strong.

The correlation coefficient value between the percentage share of seed potatoes (x2) and the weight of an average seed potato (x4) was r = −0.42. This indicates a moderate negative correlation between the percentage share of seed potatoes and the average mass of a single tuber. However, it is worth noting that this relationship is also not very strong.

The correlation coefficient value between the share of seed potatoes (x2) and the average mass of a single seed potato (x4) was only r = 0.02. This indicates a very weak positive correlation between these characteristics; however, this relationship is extremely weak.

Based on the obtained correlation coefficients, it can be concluded that the percentage share of seed potatoes (x2), the number of seed potatoes (x3), and the average mass of a single seed potato (x4) do not show a strong correlation with each other. However, it is important to note that there are some relationships, although they are weak or moderate.

Therefore, there are certain areas where further research or analysis may be needed to better understand the relationships between these variables. For example, the relationship between the percentage share of seed potatoes and the number or mass of seed potatoes seems to be unclear and may require additional investigation to identify other factors affecting these variables.

4. Discussion

4.1. Impact of Ultrasound Technology on Plant Growth and Seed Potato Yield

The discussion regarding the application of ultrasonics in potato cultivation is a fascinating subject, as this technology appears to have the potential to influence various aspects of plant growth and yield, including stem count per plant, seed tuber yield, and other tuber characteristics. The results shown in Table 5 reveal that applying ultrasound treatment before planting led to a significant increase in the number of stems per plant compared to the control method. Similar results were obtained in [6]. The first significant conclusion is that the application of ultrasonics seems to have a positive impact on plant growth. Although these differences were not statistically confirmed for most varieties, the trend toward a higher stem count suggests a beneficial effect of this technology.

The number of stems per plant varied depending on the potato variety. Varieties such as 'Satina' and 'Denar' exhibited the highest number of stems per plant, suggesting their higher responsiveness to ultrasonic stimulation. On the other hand, the variety 'Zagłoba', although showing a lower number of stems compared to some other varieties, could still benefit from the effects of ultrasonics, as this trend was evident in the research sample. It is also important to note that the impact of the number of stems per plant can have significant consequences for potato yield. A greater number of stems can lead to a higher production of seed potato tubers and increased tuber mass, influencing both the quantity of tubers for planting and overall yield.

To better explain this relationship using the latest knowledge, we can delve into recent research on plant physiology and ultrasonic technology. Recent studies have shown that ultrasonic stimulation can enhance various physiological processes in plants, including cell division, nutrient uptake, and hormone synthesis [1,5]. These effects can contribute to increased branching and stem formation in plants, thereby leading to a higher number of stems per plant. Additionally, ultrasonic waves can stimulate root development, leading to better nutrient absorption and overall plant growth. Understanding these mechanisms can provide insights into how ultrasonics influence the number of stems per plant and, consequently, potato yield. Furthermore, advancements in molecular biology and genetics have shed light on the genetic basis of plant responses to ultrasonic stimulation, offering valuable insights into the specific mechanisms underlying the variability in stem number among different potato varieties. By integrating this multidisciplinary approach, we can gain a comprehensive understanding of the relationship between ultrasonics, stem number, and potato yield, leveraging the latest knowledge to optimize agricultural practices and enhance crop productivity.

The average yield of potato seedlings was nearly 38 t/ha, indicating generally high productivity. The use of ultrasonic technology before planting significantly increased the yield of potato seedlings per unit area by approximately 7% compared to the control combination. There is a lack of data on this topic in the available literature; however, it can be assumed that this effect may be attributed to ultrasonic technology, which could influence improved water and nutrient uptake by plant roots, thus contributing to better plant growth and productivity. To determine whether the increased yield of potato seedlings is caused by higher cavitation, scientific research and experiments would be necessary to understand the exact mechanism of ultrasonic technology on potato plants and their impact on potato seedling yield. Cavitation is a physical phenomenon involving the formation and collapse of gas bubbles in a liquid due to pressure changes. In agriculture, especially in the context of technologies used in plant cultivation, cavitation can be utilized in various processes such as irrigation, fertilizer mixing, or in microbiology for pathogen destruction in water [19,25–27].

The number of seedlings per unit area: The use of ultrasonic technology before planting significantly increased the number of seedlings compared to traditional technology without this treatment. This means that the use of ultrasonics before planting can increase the number of seedlings by almost 9%, which corresponds to approximately 27 thousand seedlings per hectare. Such a difference could allow for the additional planting of nearly one hectare of cultivation area.

The interaction between varieties and cultivation methods is also noteworthy. In most instances, ultrasound treatment resulted in a higher number of seedlings per hectare, indicating that this technology positively influences seedling production. Some varieties, such as 'Satina', 'Tajfun', and 'Denar', showed the greatest response to the ultrasonic treatment before planting, while other varieties reacted to a lesser extent. The conclusion drawn from these observations is that the choice of cultivation technology, including the use of ultrasonics before planting, can have a significant impact on the number of seedlings per hectare. This is important in terms of optimizing the use of the available cultivation area and achieving the desired yield.

Discussing the weight of individual potato seedlings in the context of the data from Table 9 requires considering various factors influencing this trait and their significance for yield and cultivation efficiency. The first significant conclusion is that the weight of individual potato seedlings has a significant impact on yield and the seed multiplication rate. A higher average weight of individual potato seedlings usually leads to a greater number of tubers produced from one seedling. This means that plants have the potential to produce a greater quantity of tubers, which in turn can contribute to an increase in the overall potato yield per hectare. An analysis of the data from Table 9 shows significant differences in the weight of individual potato seedlings depending on the factors studied, such as cultivation technology, potato varieties, and cultivation years. The use of ultrasonic technology before planting did not have a significant impact on this trait, but some varieties, such as 'Lord' and 'Vineta', showed a tendency to increase the weight of individual seedlings under the influence of this technology.

The interaction of cultivation technologies with the years of study also had a significant impact on the weight of individual potato seedlings. A clear beneficial effect of this technology was observed in 2017, allowing for the protection of potatoes during vegetative growth in unusual weather conditions, as well as the production of larger individual tubers to withstand drought and ensure potato reproduction in the following cycle. In summary, the weight of individual potato seedlings is a significant factor affecting yield and cultivation efficiency, and its analysis and discussion should take into account the various environmental, technological, and genetic factors of potato varieties.

The multiplication coefficient of potatoes in the context of the data from Table 8 requires considering its significance for assessing the efficiency of potato seedling production and various factors influencing this trait. The potato multiplication coefficient is an important indicator of tuber production efficiency because it reflects the number of tubers that can be obtained from one seed tuber. An analysis of the data from Table 8 shows that the average value of this coefficient in the study was 7.8. The sonication of tubers before planting contributed to a significant increase in this coefficient compared to traditional technology, from 7.5 to 8.2. The response of the studied varieties to cultivation technologies using ultrasonics before planting was varied. The 'Satina' variety showed the greatest response to this technology, while the 'Vineta' variety showed no response to the applied sonication of tubers before planting. In summary, the discussion on the potato multiplication coefficient should consider both its significance for the efficiency of potato tuber production and the impact of various factors such as cultivation technologies, potato varieties, and environmental and climatic conditions on this trait.

Potential benefits associated with the use of ultrasonics in potato cultivation may include increased potato yield, better plant resistance to environmental stress, reduced pesticide usage, and improved crop quality. In terms of crop quality improvement [28] have reported on the benefits of ultrasonically assisted vacuum impregnation for drying potato cubes, originally considered as valueless production waste. According to these authors, this approach allows for the transformation of valueless production waste into a valuable product with a high content of impregnating compounds (in this case, ascorbic acid). Furthermore, the changes induced by ultrasonics contributed to improving the energy efficiency of further processing steps, providing added value. Furthermore, the authors observe that ultrasound treatment positively affected the kinetics and energy efficiency of convective drying. The findings suggest that ultrasound could be a promising technology for enhancing potato plant growth and yield. However, additional research is required to better understand the mechanisms behind ultrasonic effects on plants and to optimize its use in agricultural practices.

In conclusion, the discussion on the use of ultrasonics in potato cultivation technologies should consider both the benefits and concerns associated with this technology, requiring rigorous scientific analysis, stakeholder dialog, and monitoring of its effects.

4.2. Analysis of the Mechanisms of Ultrasound Action

An analysis of the mechanisms of ultrasound action in the context of plant cultivation, including seed potatoes, may include the following aspects:

Improving the quality of seed potatoes by stimulating metabolic processes: Ultrasound, especially when using frequencies in the range of 20–40 kHz, can induce microscale vibrations in plant cells, which in turn leads to an increased permeability of cell membranes. This in turn can facilitate the transport of nutrients and improve the metabolism of the potato plant. An increased enzymatic activity of plant cells, including oxidase and peroxidase activity, contributes to the increased ability of plants to defend themselves against oxidative stress and supports growth processes. Ultrasound can also increase the activity of phytohormones, such as auxins and cytokinins, which stimulate the development of roots and shoots [13].

Increased nutrient uptake efficiency: Micro-scale vibrations induced by ultrasound improve soil structure, which can lead to better root system development and increased access to nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium. Our own research, as well as that conducted by other authors [6,13,29] suggest that ultrasound can improve the ability of plants to absorb minerals by increasing the efficiency of ion transport through roots. Such effects can lead to the better use of available soil resources, reducing the need for additional chemical fertilizers.

Supporting root system growth: Ultrasound can stimulate root system development by improving the structure and functioning of root cells. According to [2020] and [2024], vibrations induced by ultrasound promote the mobilization of nutrients within the soil and support the creation of a more extensive and deeper root network. This in turn can contribute to better water and nutrient accumulation, which promotes better plant growth, especially under stressful conditions.

Reducing the negative impact of agriculture on the environment: Ultrasound as a tool in agriculture can significantly contribute to sustainable development by reducing the demand for chemical plant protection products. Ultrasound technology has properties that support the natural resistance of plants to pathogens, which allows for a reduction in the use of pesticides and fungicides [6,10,11]. In addition, ultrasound can optimize the use of water and fertilizers by improving the soil structure and the efficiency of mineral uptake by plants. The increased energy efficiency of this technology, especially in comparison to traditional cultivation technology, can also contribute to reducing the carbon footprint of agriculture.

To summarize, the use of ultrasonic technology in the production of seed potatoes is a promising innovation that can contribute to increasing the quality and productivity of crops, as well as to reducing the negative impact of agriculture on the environment. By improving metabolic processes, increasing the efficiency of nutrient uptake, supporting root growth, and reducing the need for chemical plant protection products, ultrasound offers a sustainable alternative to traditional agricultural production methods.

4.3. Variability of Varieties and Their Drought Tolerance

The genetic traits of the tested varieties had a significant impact on total yield, seed potato yield, the number of seed potatoes, the average weight of a single seed potato, and the potato multiplication rate. Some varieties, such as 'Satina' and 'Denar', showed a tendency for higher seed potato production from calibrated tubers compared to other varieties. Genetic differences among the tested varieties significantly modified the yield. The most productive variety was 'Syrena', but within the same homogeneous group, other varieties such as 'Denar', 'Satina', and 'Zagłoba' also stood out. In the second homogeneous group, varieties like 'Lord' and 'Tajfun' were found, while in the least productive group were varieties like 'Vineta' and 'Owacja'. The variety 'Satina' exhibited the highest multiplication coefficient, while the remaining varieties could be divided into two homogeneous groups, suggesting differences in their reproductive abilities. Similar relationships related to the genetic characteristics of varieties were demonstrated by [11,30–33].

The benefits and limitations of cultivating the tested potato varieties may result from various factors, such as the genetic characteristics of the varieties, their adaptation to environmental conditions, yield potential, crop quality, and cultivation requirements [30–34]. Particularly important is the response of potato varieties to drought stress, which is a complex process resulting from the interaction between plant genetics and environmental conditions. According to [34], drought negatively affects plants by limiting access to water, leading to various physiological, biochemical, and morphological changes in the plant, such as restricted water availability, which inhibits physiological processes in plants such as photosynthesis, transpiration, water conduction, and mineral nutrient uptake. This results in reduced plant growth and development; disturbances in the water–electrolyte balance in plant cells, which can lead to increased oxidative stress; and alterations in water and mineral nutrient transport, leading to reduced plant ability to uptake water and mineral nutrients from the soil. This, in turn, can lead to disruptions in the transport of these substances within the plant, resulting in nutrient deficiencies and disturbances in plant functioning [30,35]. As a result, the response of potato varieties to drought stress can lead to reduced yields, a deterioration in tuber quality, and increased susceptibility to disease infections. However, plants may exhibit varying degrees of drought tolerance, depending mainly on their genetic resistance and degree of adaptation to environmental conditions. Therefore, breeding and selecting potato varieties with greater drought resistance are crucial for ensuring stable production in changing climate conditions.

The overall benefits and limitations associated with cultivating specific varieties are as follows: high yield potential; some varieties may exhibit higher yields compared to others, resulting in increased harvests per unit area; resistance to diseases and pests;

good crop quality; and cultivation flexibility [30–32]. Limitations of the studied varieties include, among others, low environmental resistance, such as low resistance to drought, excessive humidity, or extreme air temperatures, which can lead to reduced tuber yields; susceptibility to diseases or pests, increasing the risk of infection-related losses; some varieties may require specific soil, climatic, or fertilization conditions, which can increase production costs or limit their application to certain regions; and low stress tolerance and less flexibility in adapting to changing environmental conditions, which may result in decreased yield performance in case of stress occurrences [32–36].

The benefits and limitations of cultivating individual potato varieties are diverse and depend on various factors. Therefore, selecting the appropriate variety for cultivation should take into account local environmental conditions, production goals, and the availability of agricultural technologies and plant protection. It is also important to consider the preferences of producers to understand their preferences regarding selected varieties in combination with ultrasound technology [28,32].

The future prospects for the potato varieties studied depend on various factors, including climate change resilience, sustainable production, breeding innovations, enhanced disease resistance, and consumer preferences. Developing varieties resilient to changing weather conditions is crucial, along with sustainable production practices and innovations in breeding techniques. Increasing disease and pest resistance can mitigate losses, while meeting consumer preferences for taste, texture, and nutrition can boost market demand. Overall, continuous adaptation to new challenges and innovations in potato cultivation are essential for future success. Scientists are encouraged to continue researching the impact of different potato varieties combined with ultrasound technology and to monitor progress in their agricultural application.

4.4. Effect of Environmental Factors on Potato Yield and Its Characteristics

Environmental conditions play a crucial role in determining the efficiency of potato cultivation. Key factors such as soil moisture, temperature, sunlight exposure, and nutrient availability greatly influence plant development and tuber production.

Optimal environmental conditions conducive to plant growth can lead to increased yield, a greater number of tubers, their mass, and quality. On the other hand, adverse conditions such as drought, excessive moisture, or nutrient deficiency can limit plant growth and result in reduced yield and tuber quality. Therefore, monitoring environmental conditions and the proper management of them are crucial for achieving optimal potato yield and quality. The discussion on the impact of environmental conditions on potato yield and its indicators can be crucial for understanding the factors influencing cultivation efficiency. Various environmental factors, such as weather conditions (e.g., rainfall, temperature, sunlight, wind) and soil factors (e.g., soil structure, pH, nutrient content, moisture), can significantly affect potato yield [35].

The average potato tuber yield in the experiment was notably high; however, it was significantly influenced by the variability in weather conditions across the study years. In 2015, yields were considerably lower compared to other years, likely due to unfavorable weather and soil conditions. The highest yield was recorded in 2016, a year characterized by weather conditions that were particularly favorable for potato cultivation. In 2017, while yields exceeded those of 2015, they remained below the levels achieved in 2016, as water supply during the growing season was optimal but not as favorable as in the previous year. Similar findings were reported by [37], who highlighted the critical role of meteorological conditions in shaping tuber yield structure. Their research revealed that weather conditions during the potato growing season played a crucial role in determining tuber yield. The highest yields, both for commercial and seed potatoes, were achieved in years with adequate rainfall and evenly distributed moisture throughout the growing season. In contrast, dry periods during vegetation growth were less conducive to achieving high yields in these cases.

The potato varieties under study also showed a varied response to soil and climatic conditions during the research period. It was precisely the unusual weather patterns that led to significantly different yields among the tested varieties. In the group of varieties with the highest yields of potato tubers, 'Denar', 'Lord', 'Satina', and 'Syrena' were included. In the next group, with homogeneous yields, the varieties 'Vineta', 'Tajfun', and 'Zagłoba' were found, while the variety with the lowest yield of potato tubers was 'Owacja'.

Changes in the number of tubers per hectare were also observed in subsequent years of this study. The highest number of tubers was obtained in 2017, characterized by variable thermal–humidity conditions, while the lowest was in the dry year of 2015. These results suggest that atmospheric conditions and other environmental factors can have a significant impact on tuber production. Was noted [34] also a similar response to weather conditions. Was demonstrated [32] that drought activates defense mechanisms, such as the accumulation of osmotic substances, antioxidant production, the closure of stomata, and leaf structure changes to reduce transpiration. Physiological drought can disrupt plant metabolism, triggering the accumulation of osmotically active compounds such as proline and sugars, reducing photosynthetic efficiency, and altering the activity of enzymes responsible for carbohydrate, amino acid, and lipid metabolism.

Climatic and environmental factors had a pronounced impact on the average weight of individual tubers. The highest tuber weight was recorded in 2017, a year marked by atypical weather patterns that likely enhanced the rate and intensity of tuber development. Conversely, the lowest multiplication coefficient was obtained in 2015 during the drought period.

The varied responses of potato varieties to changing weather conditions can be attributed to their genetic differences and ability to adapt to environmental changes [32–34,38,39]. Several key factors contribute to this variability, including the following:

(a) Genetic traits: Different varieties possess unique genetic characteristics that influence their tolerance to environmental stresses, such as drought, excessive moisture, extreme temperatures, or susceptibility to diseases and pests. Certain varieties may exhibit greater resilience to specific conditions than others.
(b) Local adaptation: Some varieties are naturally better suited to the specific climatic and soil conditions of a given region, enhancing their performance under those particular circumstances. Varieties well suited to certain conditions may show better tuber yields compared to varieties less adapted to these conditions.
(c) Genetic flexibility: some varieties may be more genetically flexible, meaning they can better respond to variable weather conditions by quickly adapting to changes in the environment.
(d) Genotype–environment interactions: the variety's response to weather conditions may also result from interactions between genetic traits and environmental conditions, meaning that the influence of weather conditions on plants can be modified by their genotype [35–38,40].

As a result, different potato varieties may exhibit varied reactions to weather conditions due to differences in their genetics, environmental adaptation, and genetic flexibility. Therefore, it is important to use different varieties depending on local growing conditions to maximize yield and crop resilience to variable weather conditions [40].

4.5. Correlations Between Potato Tuber Characteristics

The yield of seed potatoes showed a high positive correlation with the number of seed potatoes, as well as with the average mass of a single seed potato and the potato multiplication ratio. This coefficient exhibited a strong positive correlation with the yield of seed potatoes, their number, and with the average mass of a single tuber.

Based on the obtained correlation coefficients, it can be concluded that the percentage share of seed potatoes, the number of seed potatoes, and the average mass of a single seed potato do not show a strong correlation with each other. However, it is important to note that there are some relationships, although they are weak or moderate. Therefore, there are certain areas where further research or analysis may be needed to better understand the relationships between these variables. For example, the relationship between the percentage share of seed potatoes and the number or mass of seed potatoes seems to be unclear and may require additional investigation to identify other factors affecting these variables.

The correlation matrix offers valuable insights into the relationships between various variables, serving as a useful tool for guiding future studies, experiments, and agricultural practices. A moderately positive correlation was observed between the number of stems and several key parameters, including total tuber yield, seed potato yield, the number of seed potatoes per unit area, and the average weight of individual seed potato tubers.

Research by [41] highlights that increasing the number of stems per plant can contribute to a higher seed potato yield, as each stem has the potential to produce more tubers. Similar findings have been reported [37,40], further supporting the notion that stem proliferation positively influences tuber production. These studies underscore the importance of optimizing cultivation practices to enhance stem growth and, consequently, potato yield.

According to [42], an increase in the number of stems could potentially affect the coefficient of multiplication, as a higher number of stems may indicate a greater total mass of harvested tubers, which could lead to a decrease in the multiplication coefficient if the mass of the harvested potato yield does not increase proportionally to the mass of seed potatoes.

The seed potato yield showed a high positive correlation both with their number and with the average mass of a single seed potato. Meanwhile, the potato multiplication coefficient also exhibited a strong positive correlation with both the seed potato yield, their number, and the average mass of a single tuber. The correlation coefficient value between the percentage of seed potatoes and the average mass of a single seed potato was $r = -0.42$. This indicates a moderately negative correlation between the percentage of seed potatoes and the average mass of a single tuber. However, it is worth noting that this relationship is not very strong. The correlation coefficient value between the number of seed potato tubers and the average mass of a single seed potato turned out to be exceptionally weak. These findings are confirmed by research conducted by [37,39].

Recent studies by [43] have shown a significant positive correlation between the number of stems per potato plant and the total yield of tubers. They suggest that increasing stem density through optimal planting densities could enhance tuber yield without compromising tuber quality.

Additionally, research by [44] found that the percentage of seed potato tubers in a crop has a strong negative correlation with tuber size distribution. This highlights the importance of seed potato quality and planting practices in achieving desired tuber characteristics.

Furthermore, the Standardization of Seed Potato (GE.6) [45] revealed that the average mass of one seed potato tuber is positively correlated with tuber yield but negatively correlated with tuber dry matter content. This suggests a trade-off between yield and quality that breeders and growers should consider in cultivar selection and management practices.

Was highlighted [46] several key parameters as effective indicators of potato seedling quality, including stem diameter, leaf count, fourth-leaf length on the main stem, leaf surface area, number of tubers per plant, root dry weight, and total dry weight. Their findings demonstrated that days after transplanting (DATs) significantly influenced these morphophysiological traits, with 45 DATs identified as the optimal time for estimating seed potato yield. Furthermore, collecting data biweekly was found to be as reliable as weekly harvests, suggesting an efficient schedule for monitoring growth parameters.

Future research should focus on exploring the relationships between stem number, potato yield, seed potato proportion, and the average mass of individual seed potatoes to better understand their combined impact on overall potato productivity. Investigating these traits in detail could pave the way for improved breeding programs and agronomic practices aimed at maximizing both yield and quality in potato cultivation [24]. Additionally, alternative factors and underlying mechanisms influencing these traits should be considered in future studies to develop a more comprehensive understanding of potato growth dynamics and yield optimization strategies.

4.6. Uncertainty and Error Analysis

Definition of uncertainty and errors in the context of research: Uncertainty in scientific research refers to the degree to which measurement results may differ from true values. This means that even when using the best measurement techniques and tools, there is a certain margin of inaccuracy that results from limitations of the methodology, the equipment used, or experimental conditions [24]. Uncertainty and error analysis is an important element of assessing the reliability of research results, enabling their more comprehensive interpretation. In order to increase the precision and accuracy of the research, a detailed assessment of potential sources of error was carried out, and strategies for minimizing uncertainty were applied.

In practice, uncertainty reflects the precision of measurements, and its analysis allows for determining to what extent the obtained results are reliable and repeatable.

Errors in research can be divided into two main categories, namely systematic errors resulting from the incorrect calibration of equipment, the inadequacy of the mathematical model used, or other repeatable factors that cause a constant deviation of results in one direction.

The other category is random errors related to unpredictable changes in the measurement process, such as environmental fluctuations, biological variability, or the influence of external factors. These errors are irregular and more difficult to predict but can be reduced by increasing the number of trials or repetitions.

In the context of this research, uncertainty refers primarily to the accuracy of the obtained results regarding the effect of ultrasound on plant growth and potato yield. Error analysis, on the other hand, allows us to identify potential sources of deviation from expected results, both in the process of calibrating the ultrasonic system and in the statistical evaluation. This allows us to point out areas requiring improvement and to determine how much errors may affect the interpretation of results.

4.6.1. Uncertainty Analysis

Sources of uncertainty: The main sources of uncertainty resulted from the variability of experimental conditions:, including differences in temperature, humidity, or the homogeneity of the ultrasonic bath. Genotype variability of potatoes: natural differences in the biological responses of plants to ultrasound could introduce variability in results. Randomness of measurements: the influence of factors such as differences in sample preparation or sensor sensitivity could contribute to randomness.

4.6.2. Statistical Methods for Assessing Uncertainty

Statistical tools were used to analyze the results. An analysis of variance (ANOVA) allowed for the assessment of the variability in results between and within groups.

Descriptive statistics included the calculation of the mean, median, standard deviation, coefficient of variation, and skewness of the distribution. Measurement uncertainty: the range of uncertainty associated with the measurement devices used, including the system and the sensors for measuring photosynthesis and chlorophyll content, was determined [45].

4.6.3. Calibration of the Ultrasonic System

Before each experiment, the ultrasonic system was calibrated in the frequency range (35 kHz) and power range (70 W), which minimized systematic errors.

Monitoring of operating conditions: temperature stability and uniformity of the ultrasonic wave distribution in the bath were ensured to eliminate local differences in the intensity of the action.

4.6.4. Error Analysis

Types of errors:

(a) Systematic errors: These result from repeated inaccuracies of the measurement devices, such as minor fluctuations in the generated frequency and power of ultrasound. Careful calibration and parameter control were used, which significantly reduced these errors [46].
(b) Random errors: These originate from environmental factors, such as temperature fluctuations and differences in soil and field conditions. In the laboratory, the impact of these errors was minimized by maintaining a controlled environment and standardized test procedures [45,47,48].
(c) Error reduction strategies and repeatability of experiments: All experiments were performed with multiple replicates, which increased the accuracy of the results and reduced the influence of random errors.

Control tests: control measurements of the ultrasound power were performed using acoustic meters, confirming that the parameters were in line with the assumptions (<2% margin of error). Monitoring of environmental parameters: all key variables, such as temperature and liquid level in the bath, were continuously monitored to avoid fluctuations in the operating conditions.

4.7. Impact of Errors on the Results

Despite the presence of uncertainties and potential errors in terms of the reliability of the results, the statistical methods used showed that the results were statistically significant, and the differences between the study groups exceeded the range of random errors.

Impact on interpretation: the observed differences in seed potato quality and plant physiological parameters can be considered reliable and repeatable thanks to the effective control of potential sources of error.

4.8. Conclusions and Future Recommendations

Accuracy of the devices: The piezoelectric ultrasonic system was characterized by high precision and accuracy, which resulted in repeatability of the results. The calibration and stability of the operating frequency were crucial for the quality of the data obtained [2,9].

Minimization of errors: the constant monitoring of parameters and the use of rigorous operating procedures allowed us to reduce systematic and random errors.

Recommendations for the future: the use of advanced sensors for the real-time monitoring of ultrasound intensity and the development of automatic calibration technology could further improve the reliability of results and enable a wider application of ultrasound technology in agriculture.

Ultrasound technology, thanks to its precision and repeatability, is an innovative tool with high potential for use in sustainable agriculture.

Limitations on the Use of Ultrasound

The limitations on the use of ultrasound on higher plants result from several factors, such as the following:

1. Variability of species and variety response: Different species and varieties of plants react differently to the effects of ultrasound. This effect can be beneficial (e.g., growth stimulation) or harmful (e.g., tissue damage). This requires further detailed research on the reactions of specific plants. The developmental stage of plants, their physiological condition, or environmental stress can affect the effectiveness of ultrasound [9,35].
2. Technical limitations: The frequency and intensity and the selection of appropriate ultrasound parameters (frequency, power, exposure time) are crucial for the sonication procedure. Too high of an intensity or long-term exposure can lead to cell damage, tissue degradation, and even plant death. Ultrasound can also act unevenly on plants, especially on larger crops. Difficulties in precisely reaching all parts of the plant limit the effectiveness of this technology [9].
3. Mechanoreception allows plants to respond to ultrasonic stimuli, which can stimulate enzymatic reactions, accelerating germination and seedling development by supporting water absorption by seeds [10,12,19]. The use of ultrasound in a liquid carrier is effective, but excessive exposure can cause mechanical damage to seeds, inhibiting the germination process [9,10].
4. Possible tissue damage: The cavitation generated during the use of ultrasound can cause micro-cracks in the cell walls, which in some cases leads to the loss of cell function. The action of ultrasonic waves on plants can cause micro-damage in the internal structures of plants, such as cell membranes or conductive vessels.
5. Side effects at the metabolic level: Metabolic disorders: Ultrasound can affect the synthesis of certain chemical compounds in the plant (e.g., stress phytohormones or reactive oxygen species—ROS), which in excess can lead to the inhibition of growth or a decrease in yields. Too intense ultrasound can also induce oxidative stress, which leads to the accumulation of harmful substances in plant tissues [35].
6. Interaction with the environment: Ultrasound applied to plants can also affect soil microorganisms, which play a key role in soil fertility and plant health. A negative effect on beneficial bacteria or fungi can limit their beneficial effects. The widespread use of ultrasound in the agricultural environment may affect other organisms, such as pollinating insects and small animals, that may be sensitive to such sound waves [35,40,46].
7. Lack of standardization: Insufficient research: The technology of using ultrasound in crop cultivation is relatively new and lacks standardization in terms of best practices, which limits its widespread use in the agricultural industry. Advanced ultrasound systems can be expensive, which limits their availability to farmers with lower budgets [45,47].
8. Safety limitations: not all the effects of long-term ultrasound use on plants have been thoroughly studied, raising questions about its impact on crop quality and food safety [2,9].

One of the limitations of the mechanisms of ultrasound action with potential biological significance is the thermal mechanism, as acoustic energy absorbed by matter is converted into heat. This effect depends on the absorption and scattering of ultrasound energy. In addition to thermal effects, the passage of ultrasound waves induces numerous non-thermal actions that can be classified as cavitation and stress effects [25,26].

Another limitation is that some researchers emphasize that the effects of ultrasound on living organisms and biological tissues can lead to numerous irreversible or relatively long-lasting effects, which primarily depend on the intensity of the ultrasound and the duration of exposure. Jaime et al. [47], when testing potato plants grown in in vitro cultures, demonstrated that the application of piezoelectric ultrasound caused acute abiotic stress in potato plants. It was shown that potato plants possess a metabolic system that exhibits a strong defense response to stress, accompanied by modifications in growth-related processes. The recovery of potato plant growth occurs within four weeks after the ultrasound treatment of seedlings.

Many authors [9,10,19,25–28,35,40] highlight the limitations of using ultrasound on higher plants. In their opinion, ultrasound affects cellular and nuclear integrity. According to [13,46], the application of acoustic or ultrasonic waves under extreme conditions, such as high frequencies or prolonged exposure periods, can be harmful and even lethal to plants.

Summary: Although ultrasound has promising applications in plant growth stimulation, seed germination, and pest control, its use requires further research, especially in terms of fine-tuning parameters and assessing its long-term effects. The introduction of this technology on a large scale should be preceded by appropriate research on its effects on various plant species and ecosystems.

5. Toward the Future

Seed material is one of the most crucial inputs in potato cultivation, as it constitutes approximately 30–40% of the total cost of cultivation [4,47]. Therefore, improving seed production management is highly important for both potato producers and consumers. The use of ultrasonic technology in potato cultivation before planting has the potential to contribute to improving 'green farming' under certain conditions. The following are a few ways this could be possible:

- Increased efficiency: improving potato yield can enhance production efficiency per unit area, potentially reducing the need for new cultivation areas and minimizing pressure on the natural environment by limiting deforestation or marsh drainage.
- Resource optimization: Higher potato yields may mean better utilization of resources such as soil, water, and fertilizers. If ultrasonic technology helps plants utilize available nutrients more efficiently, it could lead to a more effective use of natural resources.
- Pesticide reduction: if ultrasonic technology aids plants in coping better with pathogens or pests, it could reduce the need for pesticide applications, contributing to environmental pollution reduction and biodiversity preservation.
- Water consumption reduction: more efficient water use by plants through ultrasonic technology could help reduce water consumption in potato crops, which is significant in water-scarce regions.
- Soil erosion minimization: increased potato yields may lead to greater soil coverage by plants, potentially reducing soil erosion by maintaining soil structure and decreasing water and wind erosion.
- Modern breeding strategies: these involve recent advancements to mitigate stress by optimizing planting density and tuber quality while balancing traits like tuber size and yield through integrated agronomic and breeding approaches.

Further research into the impact of cultivation technology, weather conditions, and different potato varieties can help develop more precise cultivation strategies. Continuously monitoring yields in various weather conditions will lead to a better understanding of yield variability and the adjustment of cultivation practices.

Research into new cultivation technologies, such as ultrasonics, and the refinement of existing methods can further increase potato production efficiency. Implementing cultivation monitoring and management systems that consider the interactions between technology, varieties, and weather conditions can assist farmers in optimizing potato production and minimizing the risk of yield loss.

6. Conclusions

The application of ultrasonication technology to potato tubers prior to planting demonstrated significant benefits, including increased total yield, seed potato productivity, and the number of seed potatoes. These results support the adoption of ultrasonication techniques as a tool for advancing sustainable agricultural practices. By enhancing crop efficiency, reducing resource consumption (e.g., water and pesticides), and minimizing soil erosion, ultrasonication contributes to the principles of 'green farming'.

Significant yield differences observed between potato varieties highlight the critical role of variety selection in achieving optimal results. Interactions between ultrasonication treatment and specific potato varieties suggest that tailoring this technology to the unique needs of each variety can maximize tuber yield, seed potato yield, and multiplication coefficients while aligning with good agricultural practices.

Weather conditions strongly influenced potato yield, including overall production, the proportion of the seed potato fraction, their number, average seed tuber mass, and multiplication coefficients. Favorable thermal–humidity conditions led to the highest yields, whereas extreme drought years caused significant yield reductions, emphasizing the need for climate-resilient strategies in potato cultivation.

Correlation analyses confirmed the multifaceted nature of factors affecting potato yield. The number and mass of tubers had the most significant impact, with stem density playing a secondary role. These findings underline the importance of interdisciplinary approaches combining breeding, planting strategies, and precision farming to balance yield quantity and quality sustainably.

Additionally, increasing the number of stems per plant showed a potential positive influence on seed potato yield and the mass of individual seed tubers. However, further research is required to deepen our understanding of these relationships, particularly regarding interactions with other factors, to facilitate the selection of potato varieties with superior productivity and adaptability to ultrasonication techniques.

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