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Impact of ultrasounds on physicochemical characteristics of potato tubers

Wpływ ultradźwięków na fizykochemiczne właściwości bulw ziemniaka

Summary. The goal of the study was to determine the effect of sonication of different potato seed material cultivars on physicochemical properties. Tuber samples from a field experiment conducted in Parczew (51°38'N, 22°54'E) in 2015–2017 were used for the study. The experiment was carried out by the method of randomized sub-blocks, in a split-plot dependent system. The first order factor were pre-planting treatments: 1) the use of ultrasounds, 2) control object without ultrasounds. The second order factor consisted of 10 potato cultivars of all earliness groups. Seed material was a subject to immerse sonication using an ultrasonic device. Following parameters were evaluated: dry matter of tubers, starch content, textural features, acidity (pH) of potato juice. Sonication contributed to the increase in dry matter and starch contents in tubers, the change in pH towards alkaline reaction, and textural parameters of raw and cooked tubers were increased.

Key words: acidity, dry matter of tubers, starch, texture, ultrasounds, potato

INTRODUCTION

Progress in the intensification of potato cultivation to improve its performance and quality can be allowed due to unconventional methods that do not enhance the chemization level in farming. The method that uses physical phenomena is the impact of ultrasounds (sonication). It is used to induce phenomena of primary or secondary character. Ultrasonic waves, depending on the frequency and intensity, allow for a non-destructive structure testing of a product [Dolatowski et al. 2007, Terefe et al. 2016, Jakubowski 2019]. The basis of ultrasonic energy in plant production may be enhancing the capacity of cell membranes, improving the tissue respiration, formation of biologically active compounds, effects on systemic enzymes, changes in the structure of colloids and their hydration, changes in tissue ionic systems. Affecting the plants or biologically active substances, their growth, cell and intracellular divisions can be stimulated, or their growth can be suspended or even inactivated [Dolatowski et al. 2007, Miłowska 2007, Zhu et al. 2012, Sawicka 2013, Zheng et al. 2013, Terefe et al. 2016, Khatkar et al. 2018].

Ultrasonic technology has already found its application in many industries, including the food industry, both for analyzing the properties and to modify the characteristics of raw materials and manufactured food [Dolatowski et al. 2007, Moza et al. 2012, Commandini et al. 2013, Miao et al. 2014, Mohammadi et al. 2014, Khatkar et al. 2018]. Nowadays, developments in ultrasonic equipment are such that it is feasible to consider commercial opportunities based on industrial-scale ultrasonic-aided extraction of bioactives with worthwhile economic gains. This technology is also applied in agriculture [Sawicka and Dolatowski 2007, Sawicka 2013, Terefe et al. 2014a, b].

The ultrasonic wave is a form of energy generated by acoustic waves with frequencies higher than 18 kHz and can propagate in gas, liquids and solids [Knorr et al. 2004, Chemat et al. 2011, Awad et al. 2012, Khatkar et al. 2018]. High-intensity ultrasounds can break down cellular structures, activate and inhibit chemical and physical changes in living cells, in food, and as a result lead to intensification of mass transfer-based processes [Nowacka and Wedzik 2016]. Nowadays, ultrasound technology has paid a lot of attention to several internal adjustment processes. Ultrasonic technology can be used to strengthen the HAD process. Ultrasonic processing can modify the structure of raw materials and food products through their physical and chemical effects, with the dominant mechanism depending on the processing conditions. The basis is the cavitation process (i.e. the formation, growth and implosion of bubbles during the propagation of sound waves in a liquid medium), both for the physical and chemical effects of ultrasound [Terefe et al. 2011, 2015]. The structure of food materials is a major determinant of sensory quality of food products, including texture and consistency that contribute to palatability [Foegeding 2007, Moelants et al. 2014]. Food structure also affects flavor release, bioavailability and digestibility of nutrients and stability of food products [Waldron et al. 1997, Asmamaw and Tekalign 2010, Awad et al. 2012, Bornhorst and Singh 2014]. Ultrasonic processing can modify the structure of food materials through physical and chemical effects.

There is little research into the subsequent effects of ultrasounds on potato tubers. Therefore, the research was aimed at demonstrating the subsequent impact of ultrasound on selected physicochemical and rheological features of potato tubers intended for food processing.

MATERIAL AND METHODS

The study involved potato tubers from a field experiment conducted in Poland (51°38'N, 22°54'E) in 2015–2017 on a slightly acidic soil with a composition of light loamy sand (Tab. 1). The field experiment was conducted using a randomized sub-block, in a split-plot dependent system. The first order factor were pre-planting treatments: a) the use of ultrasounds; b) control without ultrasounds. The second order factor accounted for potato cultivars: 'Korona' (very early); 'Nora', 'Rosalind', 'Vineta' (early), 'Baszta', 'Romula' (medium early); 'Pasja Pomorska', 'Ursus' (medium late); 'Hinga', 'Czapla' (late). The research material consisted of 8 edible cultivars and two typical starch cultivars ('Hinga' and 'Pasja Pomorska') cultivated in the area of Parczew, where the Potato Processing Plant in Przewłoka (B.E.S.T.) is located. The seed material was in EU class A.

Ultrasonic device

Tuber seed material was subject to immerse sonication using an ultrasonic bath-type device. An apparatus for ultrasonic treatment of biological materials consisted of an electronic uzm-type ultrasonic generator 25 combined with the head installed in the bottom of the tank (Polsonic, Warsaw). Its acoustic power was 200 W at a frequency of 40 kHz.

The tank lid was closed to reduce the noise emissions to the environment. Sonication was performed in an aqueous medium at a temperature of 18°C for a 7 min. Before the ultrasound treatment, the sample after prior purification laid directly on the bottom of a container that was filled with an appropriate amount of water. Operation of the sonication device was in accordance with the instructions and CE declaration of conformity. Ultrasonic waves were generated by a piezoceramic transducer and penetrated through water contained in the ultrasonic bath device. Under the influence of ultrasonic waves, variable low pressure waves with a frequency of 40,000 times per second were formed. At low pressure, millions of vacuum bubbles form and this is called cavitation process. At high pressure, the bubbles explode inward (implode), releasing enormous energy, then spread in all directions and act on all surfaces [Terefe et al. 2016].

Field research

Field studies were carried out in Parczew (51°38'N, 22°54'E) in 2015–2017. The field experiment was carried out using the method of randomized subblocks, in a split-plot dependent system, in three replications. The first-order factor was pre-planting treatments: 1) the use of ultrasound, 2) the control object, without the use of ultrasound. The second-order factor was 10 potato cultivars from all earliness groups. Potato fertilization was used at a constant level (80 kg N, 35 kg P, 100 kg K, and 25 t $\cdot$ ha^{-1} manure). Mineral fertilizers were mixed with the soil using an aggregate (cultivator + string roller). The tubers were planted by hand in the field thus prepared. Planting was carried out on April 26. Tubers were planted at a spacing of 62.5 × 40 cm. The plot was to be harvested 20 m^2. During the growing season, care of plants was carried out in accordance with the principles of good agricultural practice, and protection against Colorado potato beetle and potato blight was used with the help of available pesticides according to instruction of IOR-PIB [Wójtowicz and Mrówczyński 2017]. The harvest was carried out at the stage of technical maturity of tubers, groups of earliness of cultivars, from August 23 to September 25.

Sampling for determinations

During the harvest, tuber samples from beneath 10 plants of every plot, were collected to laboratory assessment [Lenartowicz 2013]. Following parameters were evaluated: dry matter, starch content, pH of potato juice, as well as tuber textural features.

Washed and dried tubers were cut along the axis apex – stolon. The halves were ground in a Bosch blender and then in an Ultra Turrax homogenizer. After mixing the pulp thoroughly, laboratory samples were taken for dry matter and starch content [Baryłko-Pikielna and Matuszewska 2014].

Chemical and physical analyses

The determination of the dry matter content was made using a two-stage drying method [PN/90-A-75101/03:1990] and the starch content – according to standards [PN-EN ISO 10520:2002]. To determine the pH, samples of various tuber sizes (70–140 g) were peeled, the juice was squeezed in a blender, filtered, and the clear juice was read using an electronic pH meter with combined electrode. Active (active, real) acidity of potato juice, defined as the negative logarithm of the concentration of hydronium ions (H_30^+): pH = –log (H_30^+) [Hyde and Morrison 1964].

Textural parameters

Textural parameters of potato tubers were determined with a help of texture analyzer for the strength measurements TA.XTplus by Stable Micro Systems equipped with Exponent 32 software (Stable Micro Systems Godalming UK). A set of available replaceable measuring heads included in the texture equipment was used in the work. In order to assess the mechanical strength of potato tubers, a slice of 50 mm thickness was cut out from its middle part, and then 4 cylindrical samples of 12 mm each were cut and subjected to the strength tests or hydrothermal processing (boiling). The samples intended for cooking were placed in boiling water and boiled for approximately 8 min, then cooled down in the air to ambient temperature and immediately used for the strength tests. Tuber samples (raw and cooked) were set on the texture analyzer plate and once deformed between parallel planes till 50% of their initial height at a rate of 1 mm $\cdot$ s^{-1}. The force needed to permanently deform the structure of the tuber flesh as a result of compression (hardness, height of the hardness, recoverable deformation cycle, total work cycle) was determined. Hardness was defined as the final force required to achieve a fixed deformation (on the curve it is the point of maximum deflection during the first compression cycle) [Bourne 2002, Trinh 2012].

Soil conditions

The research was conducted on Luvisols [WRB 2014]. The contents of available components in soil was as follows: phosphorus and magnesium – very high (21.0 mg of $P_2O_5 \cdot 100\ g^{-1}$ of soil, 7.03 mg of Mg $\cdot$ 100 g^{-1} of soil), nutrient solution in potassium (11.9 mg $K_2O \cdot 100\ g^{-1}$ of soil), medium – copper (7.02 mg Cu $\cdot$ kg^{-1} of soil), manganese, iron and zinc were also medium and amounted to 273.8 mg Mn $\cdot$ kg^{-1} of soil, 3761.7 mg Fe $\cdot$ kg^{-1} of soil respectively, and zinc on average was 45.96 mg Zn $\cdot$ kg^{-1} of soil. In the case of boron, the average level was about 6.17 B $\cdot$ kg^{-1} of soil (Tab. 1). The average soil acidity, in the KCl solution in 2015 and 2016 was (5.92–5.77 pH); these values allowed for the classification of the experimental soil as slightly acidic one, while in 2017, it was acidic (pH 6.6). The content of humus in the cultivated layer was low and amounted to 0.94–1.06%.

Table 1. Physical and chemical properties of soil in Parczew (2015–2017)

Year	Content of assimilable macroelements (mg · 100 g^{-1} soil)			Humus content (%)	pH (KCL)	Microelements content (mg · kg^{-1} soil)				
	P_2O_5	K_2O	Mg			Cu	Mn	Zn	Fe	B
2015	20.1	13.1	7.8	0.94	5.92	7.51	318	40.1	3760	7.24
2016	18.9	10.9	7.0	1.06	5.77	4.92	337	56.7	3925	5.28
2017	24.0	11.8	6.3	1.03	6.6	8.99	166	41.1	3600	6.04
Average	21.0	11.9	7.03	1.02	6.09	7.02	274	46.0	3762	6.17

Source: Own experiment results made in the Laboratory Central of Agro-Ecological the University of Life Science in Lublin

Meteorological conditions

The weather course during the years of study was diverse. The year 2015 was warm with a deficiency of precipitation in July, August, and September. The year 2016 was characterized by temperatures above the long-term average and rainfalls in May and July above, while in the remaining months of the growing season, below the long-term standard. In 2017, the air temperature was above, whereas rainfalls, except May and July, when the excess of rainfalls was recorded, were below the long-term average (Fig. 1).

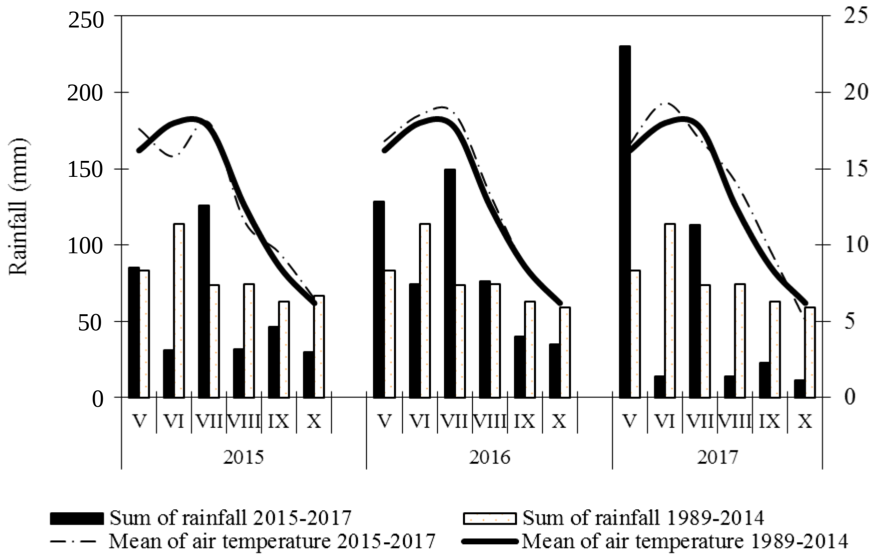

Fig. 1. The distribution of air temperature and precipitation during the growing potatoes by the meteorological station in Włodawa

Statistical analyzes

Statistical analyzes were based on three-factor analysis of variance (ANOVA – Analysis of variance) and multiple tests of T-Tukey's. The models of analysis of variance with the main effects of the factors studied and their interactions were used. The detailed analysis only dealt with the main effects. Statistical analysis of the test results was performed using Statistica 8.0 at a significance level of p = 0.05 (Statistica 8.0). T-Tukey's multiple comparison tests enabled detailed comparative analyzes of averages, by isolating statistically homogeneous medium groups (homogeneous groups) and determining the so-called the smallest significant mean differences (NIR), which in Tukey's tests are marked by HSD (Tukey's Honest Significant Difference) [Trętowski and Wójcik 1998]. As part of the descriptive statistics, generalized (relative, absolute) coefficients of variation for the whole experiment (for each variable) CV (coefficient of variation – in %) or RSD (relative standard deviation) were calculated. They are measures of random variation in conducted experiments. Explanations for all tables contain the most important elements of variance analyzes, including calculated probabilities (so-called p-value) related to applied test functions F (F-Snedecor or Fisher-Snedecor). The calculated p-values determine the significance and magnitude of the impact of the studied factors on the differentiation of the results of the analyzed variables, by comparing them with the most frequently accepted levels of alpha significance (0.05, 0.01).

RESULTS

Sonication of seed material significantly increased the content of dry matter of potato tubers. The genetic features of cultivars also proved to be the factor differentiating the tuber dry matter. The largest dry matter of tuber was characterized late 'Hinga', while the smallest – very early 'Korona'. Cultivars: 'Hinga', 'Pasja Pomorska', 'Ursus' and 'Romula' as well as 'Nora', 'Rosalind', 'Vineta', 'Korona', 'Baszta' and 'Czapla' were in two homogeneous groups in terms of this feature. Meteorological conditions during the study significantly shaped this feature, as well. The largest dry matter of tubers was recorded in 2016 with at the optimal precipitation and air temperature above the from many-years norm, the lowest – in the 2017, dry year (Tab. 2).

The tested cultivars showed a varied response to the use of ultrasound on the seed potatoes. An increase in dry matter content, under the influence of this treatment, was observed in the following cultivars: 'Korona', 'Baszta', 'Romula', 'Czapla' and 'Ursus', while in the 'Nora' and 'Pasja Pomorska' a decrease in the value of this trait was noted. Other cultivars did not show a significant reaction to sonication of seed potatoes (Fig. 2).

Starch content was significantly higher in objects with the ultrasound application, than in the control combination. The highest starch concentration characterized late 'Hinga', whereas the smallest – early 'Vineta'. Among the studied cultivars od potato, three homogeneous groups can be distinguished in terms of the examined characteristic: 'Hinga' and 'Pasja Pomorska'; 'Czapla', 'Romula' and 'Ursus'; 'Nora', 'Rosalind', 'Korona', 'Baszta' and 'Vineta'. The highest starch content in tubers was achieved in 2015 with optimally distributed rainfalls and temperatures exceeding the long-term average and the smallest – in dry 2017 year (Tab. 2).

Table 2. Content of dry matter, starch, acidity of potato tubers depending on the ultrasound, cultivars and years

Experimental factors		Dry matter (%)	Starch content (%)	Acidity (pH)
Technology	control (without ultrasounds)	22.0[a]	14.5[b]	6.23[b]
	ultrasounds	24.6[b]	15.5[a]	6.32[a]
	HSD $p_{0.05}$	1.5	0.4	0.06
Cultivars	'Nora'	22.2[b]	14.1[c]	6.29[a]
	'Rosalind'	21.5[b]	13.8[c]	6.28[a]
	'Vineta'	20.5[b]	12.2[cd]	6.26[a]
	'Korona'	19.4[b]	12.9[c]	6.26[a]
	'Baszta'	22.5[b]	13.4[c]	6.45[a]
	'Romula'	23.8[a]	15.3[b]	6.14[b]
	'Czapla'	22.5[b]	15.6[b]	6.31[a]
	'Pasja Pomorska'	26.3[a]	17.3[a]	6.20[a]
	'Hinga'	30.5[a]	19.2[a]	6.26[a]
	'Ursus'	23.7[a]	16.2[b]	6.32[a]
	HSD $p_{0.05}$	7.4	2.0	0.28
Years	2015	23.0[bc]	17.2[a]	6.28[a]
	2016	24.8[a]	14.1[b]	6.30[a]
	2017	22.0[b]	13.6[c]	6.27[a]
	HSD $p_{0.05}$	1.7	0.3	ns*
Mean		23.3	15.0	6.28

* not significant at $p_{0.05}$

Letter indicators at averages determine the so-called homogeneous groups (statistically homogeneous). The occurrence of the same letter pointer at averages (at least one) means that there is no (no) statistically significant difference between them. The sizes of HSD perform an auxiliary role, allowing to quantify the differences between means in a quantitative way.

Potato juice pH values ranged from 6.14 to 6.45. Under the influence of ultrasounds, the juice pH changes towards alkaline, was occurred. The most acidic juice was obtained from tubers of the Romula cultivar, while the least – from the tubers of the 'Baszta'. 'Nora', 'Rosalind', 'Vineta', 'Czapla', 'Hinga', 'Ursus', 'Baszta' and 'Pasja Pomorska' were in the same homogeneous group in terms of the value of this trait. Weather conditions during the years of study did not differentiate this trait value (Tab. 2).

Sonication of tubers before planting of potato contributed to the increase in the value of such parameters of child tubers as: hardness of raw and boiled tubers, their compressive depth. The deformation of raw and boiled tubers was remarkably higher than in the control object. Total work cycle incurred on compressing of raw tubers were remarkably than in the control object while value of this feature for boiled tubers did not depend significantly on the sonication process (Tab. 3).

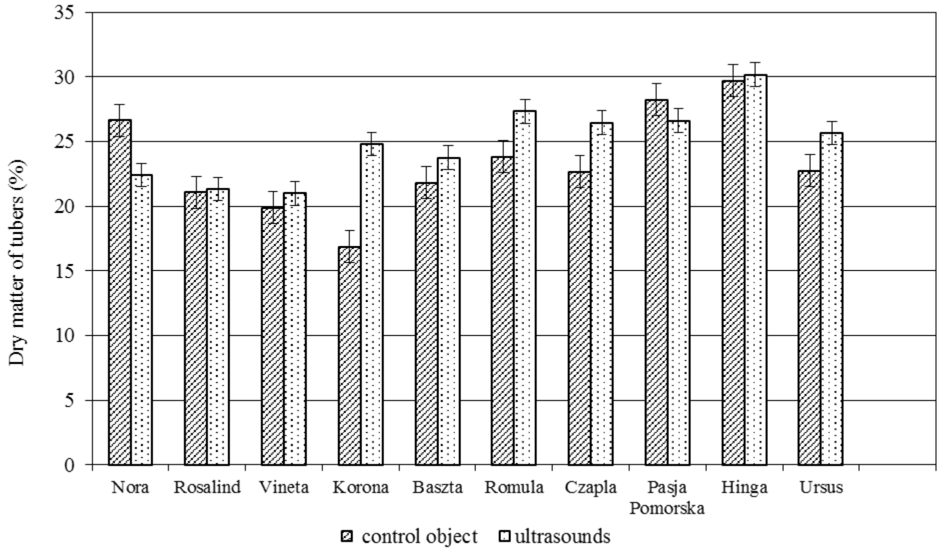

Fig. 2. Effect of cultivars and ultrasonic on the dry matter of the raw potato tubers

Texture is a sensory attribute of uppermost importance for the preference of potatoes. Genetic factors significantly determined the majority of tuber texture parameters. ‘Romula’ required the largest work to overcome the hardness of the raw potato parenchyma, while ‘Rosalind’ − the smallest; with 4 homogeneous groups distinguished among the examined cultivars: ‘Nora’, ‘Korona’, ‘Hinga’, ‘Ursus’; ‘Vineta’, ‘Baszta’, ‘Czapla’; ‘Rosalind’ and ‘Pasja Pomorska’. In the case of boiled tubers, the highest value of this trait was recorded for medium early ‘Baszta’, and the lowest – medium late middle late ‘Pasja Pomorska’; with the following cultivars: ‘Nora’, ‘Vineta’, ‘Baszta’, ‘Romula’, ‘Czapla’ and ‘Ursus’; ‘Korona’, ‘Rosalind’, ‘Hinga’ and ‘Pasja Pomorska’ proved to be homogeneous in this characteristic (Tab. 3).

The cultivar requiring the greatest compressive depth turned out to be the ‘Romula’ cultivar, and the smallest – ‘Ursus’; with the following cultivars: ‘Rosalind’, ‘Vineta’, ‘Korona’, ‘Baszta’ and ‘Czapla’; ‘Nora’, ‘Baszta’ and ‘Hinga’; ‘Pasja Pomorska’ and ‘Ursus’ were homogeneous due to this feature. In the case of boiled tubers, tested cultivars were not significantly different in respect of this parameter texture value (Tab. 3).

Recoverable deformation cycle was depended form genetic traits. For raw tubers, ‘Nora’ and ‘Romula’ required the most work to overcome the crush resistance of the tubers, and ‘Hinga’ required the least work. In the case of boiled tubers, the largest deformation work was required by ‘Baszta’ and the smallest by ‘Hinga’. For cooked tubers, the ‘Baszta’ cultivar required the most deformation, and ‘Hinga’ – the least; with the following cultivars: ‘Vineta’, ‘Korona’, ‘Czapla’, ‘Pasja Pomorska’ and ‘Urus’ in the same homogenic group (Tab. 3).

Table 3. Values of rheological properties of potato tubers depending on the ultrasound, ultivars and years

Experimental factors		Hardness work cycle (N)		Compression depth (mm)		Recoverable deformation cycle (mJ)		Total work cycle (mJ)	
		raw tubers	cooked tubers	raw tubers	cooked tubers	raw tubers	cooked tubers	raw tubers	cooked tubers
Technology	control	82.18^{b}	10.84^{b}	8.25^{b}	11.29^{b}	464.85^{b}	80.43^{b}	488.89^{a}	92.83^{b}
	ultrasounds	85.04^{a}	12.78^{a}	8.95^{a}	13.11^{a}	482.02^{a}	142.93^{a}	437.98^{b}	93.51a
	HSD $p_{0.05}$	2.51	0.35	0.26	0.37	14.20	3.35	14.42	ns*
Cultivars	‘Nora’	97.80^{b}	11.91^{a}	8.32^{c}	12.36a	559.47^{a}	102.30^{d}	574.74^{a}	70.26^{e}
	‘Rosalind’	68.80^{a}	9.65^{b}	8.57^{b}	12.27a	458.36^{b}	93.01^{e}	466.08^{c}	60.78^{f}
	‘Vineta’	79.23^{d}	16.56^{a}	8.71^{b}	11.94a	538.65^{a}	117.29^{c}	523.34^{b}	97.74^{d}
	‘Korona’	88.82^{c}	10.07^{b}	9.15^{b}	11.89a	435.61^{bc}	114.82^{c}	445.95^{c}	36.09g
	‘Baszta’	75.57^{d}	21.59^{a}	8.33^{c}	12.08a	477.45^{b}	161.59^{a}	449.97^{c}	133.44^{c}
	‘Romula’	108.75^{a}	13.89a	10.73^{a}	11.95a	559.08^{a}	150.15^{b}	574.35^{a}	70.73e
	‘Czapla’	74.98^{d}	12.28^{a}	8.67^{b}	12.21a	443.09^{b}	117.51^{c}	447.55c	142.04^{b}
	‘Pasja Pomorska’	71.18e	4.23^{b}	7.80^{cd}	12.01a	464.81^{b}	115.32^{c}	454.31c	165.88^{a}
	‘Hinga’	84.46^{c}	7.30^{b}	8.16^{c}	12.62a	360.83^{c}	29.25^{f}	450.84^{c}	22.56^{h}
	‘Ursus’	86.53^{c}	10.62^{a}	7.59^{d}	12.70a	437.01^{b}	115.59^{c}	421.06^{d}	132.20^{c}
	HSD $p_{0.05}$	6.27	11.81	0.65	ns	35.51	8.37	36.06	6.99
Years	2015	83.14^{a}	11.81^{a}	8.56^{a}	12.19a	473.33^{a}	108.81^{a}	478.11^{a}	92.65^{b}
	2016	84.72^{a}	11.80^{a}	8.60^{a}	12.22a	473.54^{a}	114.16^{a}	435.03^{b}	94.41^{a}
	2017	82.98^{a}	11.81^{a}	8.65^{a}	12.20a	473.44^{a}	112.07^{a}	477.16^{a}	92.46^{b}
	HSD $p_{0.05}$	ns	ns	ns	ns	ns	ns	10.01	1.89
Mean		83.61	0.89	8.60	12.20	473.44	111.68	480.82	93.17

Designations as in table 2

For raw tubers, ‘Nora’ and ‘Romula’ required the most work to overcome the crush resistance of the tubers, and ‘Ursus’ required the least work. In the case of cooked tubers, the differences between cultivars turned out to be insignificant in terms of this characteristic (Tab. 3).

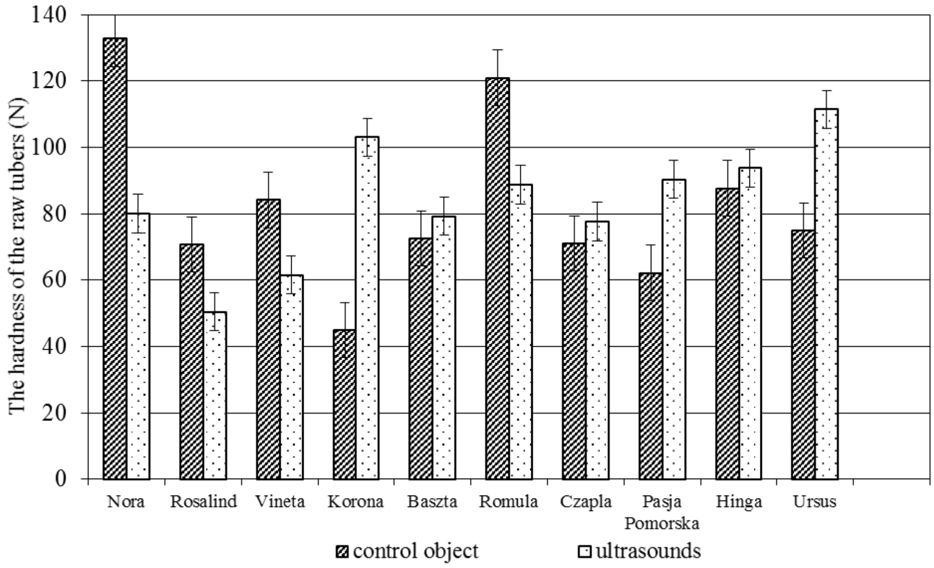

Fig. 3. Effect of ultrasounds and cultivars of the hardness of the raw potato tubers

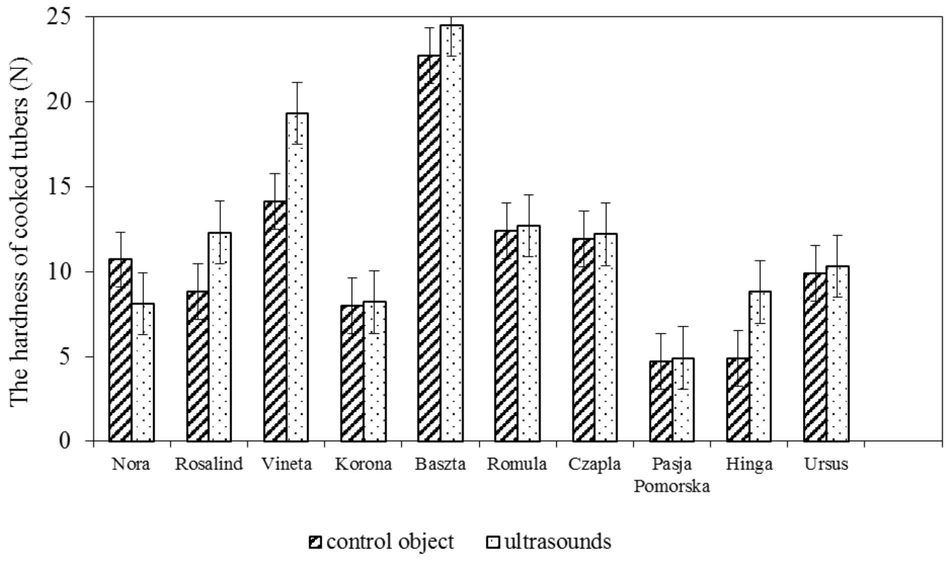

Fig. 4. Effect of ultrasounds and cultivars of the hardness of the cooked potato tubers

The influence of weather conditions on the rheological parameters was significant only for the total deformation work, both in the case of raw and boiled tubers. Raw tubers reached higher value of this parameter in 2015 – warm and optimal in terms of rainfall, whereas boiled tubers in 2016 (Tab. 3).

Tested potato cultivars showed different reaction to ultrasounds in the case of hardness of raw tubers. Cultivars: 'Nora', 'Rosalind', 'Vineta', and 'Romula' reacted with a significant decrease in this feature value, while 'Korona', 'Pasja Pomorska', and 'Ursus' – with its increase. Cultivars: 'Baszta', 'Czapla' and 'Hinga' showed no significant response to this factor (Fig. 3).

Some different reaction of cultivars towards the application of ultrasounds was recorded in the case of hardness of boiled tubers. 'Nora' responded with a significant decrease, while cultivars: 'Rosalind', 'Vineta', 'Baszta' and 'Hinga' – with an increasing in the value of this feature due to the tuber sonication (Fig. 4).

DISCUSSION

Following the pre-planting sonication, produced potato tubers had altered physical and chemical properties, as there was an increase in the starch content as well as a change in the raw tuber tissue reaction. The reasons for this should be seen in the stimulating influence of low-frequency of ultrasounds and the intensity on cellular processes that occur prior to planting. In opinion of many authors [Zhu et al. 2012, Zheng et al. 2013, Wu and Zhou 2018], effects of ultrasounds on substances or living organisms depend on the properties of the acoustic field (medium or such its fragment, in which the wave propagation phenomenon occurs). Teixeira da Silva and Dobránszki [2014] and Dobránszki et al. [2019] confirm that there is evidence that sonication using low sound frequencies (only tens of Hz) to as high as ultrasound (tens of kHz) can increase organogenesis. These authors better explained the genetic mechanism underlying the physiological response of potato to abiotic stress (US). They proved that some processes evolved over time after applying abiotic stress to potato explants *in vitro*, and thus provided guidance on the time dynamics of DEG – based on enzymatic functions in response to this abiotic stress which was the use of ultrasonic sonication. In the experiment, low-frequency and medium-intensity ultrasound exerted a stimulating effect on the content dry matter and starch by accelerating the assimilation of plants, improving their physiological condition and strengthening the development and growth of their cells. Asmamaw and Tekalingn [2010] proved that cultivars with a higher dry matter concentration maintained better quality than cultivars with a lower dry matter concentration.

In this study, an increase in dry matter and starch contents under the influence of ultrasound treatment on the seed potatoes, was achieved. In summary, ultrasound treatment at 40 kHz for 7 min promoted the increase in dry matter and starch content in potato tubers, maintaining the pH of potato juice and increasing or maintaining the structure hardness and resistance of raw tubers, as well as after cooking. Results of Zhu et al. [2012] upon the starch structure confirm this effect, which was explained by the crystalline structure of amylose compared to amorphous structure of amylopectin lamella. In their opinion, ultrasounds exert a wide-range influence on the structure of potato starch. The crystalline structure of B type and crystallinity are barely visible. Lamella crystallinity is disordered, which reduces the molecular order in the long term, whereas amylose is much more exposed as compared with the amorphous amylopectin lamella.

Acidity is one of the basic parameters determining the quality of food and is characteristic of potato products. Changes in acidity may provide information about its freshness as well as about adverse processes occurring in the product (e.g. as a result of incorrect production or improper storage). The active acidity of potato juice increased under the influence of ultrasound applied on the tubers before planting of potato. According to Lewandowicz et al. [2012], active acidity depends primarily on the strength of the acid present in the solution. This may indicate the strength of the acids (citric, chlorogenic) present in the solution. Hayde and Morrison [1964] found that the pH of potato juice negatively correlates with a reduction in the level of sugar in tubers and is therefore an excellent indicator to assess the quality of products fried from potatoes (chips, fries).

Lewandowicz et al. [2012] stated that active acidity of the juice and the content of juice components from the point of view of food and pharmacy are important. The inhibition of acidity by ultrasound results mainly from the inactivation of enzymes caused by physical and chemical cavitation. Pan et al. [2020] proved that on the one hand, high-energy free radicals produced by cavitation change the spatial conformation and biological activity of an enzyme by reacting with some amino acid residues. On the other hand, the shock wave and shear forces generated by crumbling cavitation bubbles disrupt hydrogen bonding and van der Waals interactions in the polypeptide chain as a result of modification of the secondary and tertiary structure of the enzyme molecules. They also showed that ultrasound inhibits enzymatic browning and maintains fruit quality in freshly sliced potatoes and freshly sliced apples. In addition, ultrasounds have been shown to be effective in reducing malonaldehyde content and maintaining cell wall integrity in freshly cut potatoes, and in preserving antioxidants and extending the shelf life of boiled potatoes. Most of the analyzed features, essential in the potato production, is subject to a high phenotypic variability depending on the influence of habitat and genotype. Assessed characteristics of potato tubers were significantly modified by genetic variation of cultivars. According to Sawicka [2013], besides the genetic variability of plants, an environmental variability occurs in parallel. The most important reasons for this variation are quality of seed potatoes (health, size, physiological and chronological age), heterogeneity of the soil environment, diversity of the impact of meteorological conditions (temperature, light wavelength, intensity, water supply) [Sawicka et al. 2015]. Indicators of their physiological aging, method for assessing the rate of physiological aging of different potato genotypes as a quick and effective diagnostic tool for the assessment of physiological aging rate at various stages of tubers, and possibility of predicting their further aging as a function of temperature and environmental factors, are rather searched for [Rykaczewska 2010].

Diversity of the environment, in which potato plants grow, modifies the self-regulation processes within the potato plant, which in turn affects the efficiency of ultrasounds [Sawicka and Dolatowski 2007, Soria and Villamiel 2010, Miao et al. 2014]. Varied response of particular cultivars on factors modifying the physicochemical properties of mother and child tubers, is well-known [Rykaczewska 2010, Sawicka 2013].

The strength tests, including compression and deformation, directly relating to properties such as hardness and the level of the hardness, were very good indication of mechanical properties of potato tubers. The texture is, according to Zhu et al. [2012], Zheng et al. [2013], Dolik and Kubiak [2013], a multidimensional property resulting from the molecular, microscopic and macroscopic structure of raw materials and products. It consists of, among others: hardness, elasticity, chewiness, flexibility and many others. The results of the raw and cooked potato tubers examined by us, in terms of texture, were characterized by high variability, which indicates a much higher sensitivity of instrumental measurements compared to human assessment of texture [Thygesen et al. 2001].

The strength tests, among others compression and crushing, directly relating to the characteristics of potato tubers such as hardness, the hardness solids, and deformation work, are good indicators of the physical properties of tuber parenchyma. The maximum compression and crushing force were an indicator showing the differences in hardness of tuber parenchyma of individual potato cultivars. Early cultivars with higher parenchyma hydration and lower starch level were characterized by a lower tuber resistance to compression and squeezing, indicating a softer tissue resulting from the presence of large intercellular spaces filled with air. Sawicka and Dolatowski [2007] found that potato is a viscoelastic material with a special share of elastic features. Rheological properties of a food (mechanical and geometric traits, viscosity etc.) may be in many cases considered secondary, however, if they do not meet the consumer's expectations, a product cannot be accepted. Rheological properties of potato tubers resulting from their structures can be created by environmental and agronomic factors, genetic features of cultivars, storage, or processing procedures. A proper shaping of rheological characteristics of food products made from potato is of particular importance in the case of special purpose foods, for which for various reasons, to eliminate the selected components without disturbance of their sensory and functional characteristics, is still searched. According to Trinh [2012], Texture Profile Analysis is a very popular instrumental test, but many of the original TXTA parameters need to be redefined to capture human sensory perception more accurately.

Due to the fact that the model assessing the product model is important in the analysis of sensory data, because potato tubers are somewhat heterogeneous, even when grown under controlled conditions and sorted in terms of size and density. So different assessors can actually get "different" products. Thybo and Martens [2000] was analyzed the reliability and performance of sensory assessors in texture profiling using one-dimensional (ANOVA) and multidimensional procedure using discriminatory least squares partial regression (DPLSR). This modeling removed differences in assessor levels. It has been shown that flouriness and firmness are the most reliable attributes of tuber texture, and elasticity and chewing – as the least reliable attributes [Thygesen 2001]. The study of rheological features using a texture meter gave more stable results than sensory evaluation.

The maximum compression and crushing force were an indicator showing the differences in hardness of tuber parenchyma of particular potato cultivars. Early cultivars with higher parenchyma hydration and lower starch level were characterized by a lower tuber resistance to compression and squeezing, indicating a softer tissue resulting from the presence of large intercellular spaces filled with air. Mechanisms, which may cause ultrasounds and their effects, are still intriguing. Possible mechanisms include direct and indirect mechanical effects such as acoustic streaming, acoustic radiation, and surface wave propagation, fluid flow induced by the circulation and distribution of nutrients, oxygen, and signaling molecules. Effects induced by conversion the acoustic wave energy into heat are usually neglected, but heating the sensor can potentially affect the stimulation in some *in vitro* systems, depending on the conjugation conditions. These studies, although general biological effects should not be equated, are very interesting referring to the specific mechanisms of action [Moza i in. 2012].

The diversity of current experimental research makes, however, that these analyses are very complicated as to phenomena such as: heating, heterogeneity of sound intensity transducers in the nearby field, resonance in the transmission and reflection, as well as formation of standing waves [Ozunan et al. 2011, Moza et al. 2012, Zhu et al. 2012, Commandini et al. 2013, Zheng et al. 2013]. The study shows that tested traits were also influenced by habitat conditions and the amplitude of the stimulus applied to the tuber parenchyma. The challenge for the future is therefore the engineering of experimental set designs, in which various mechanical phenomena induced by ultrasounds can be controlled [Liu et al. 2017]. This is a prerequisite to assess the biological effects of various phenomena in relation to particular parameters such as intensity, frequency, and working cycle. Finally, and despite the improved equipment design and the higher efficiencies of Polish systems currently used for other applications, a better understanding of the complex physicochemical mechanism of high-intensity ultrasound action and its effect on technological and functional properties of food would also contribute to reinforce the future presence of ultrasonic technologies in the food industry.

Response of studied cultivars towards application of ultrasounds, in the-dry matter of tubers and hardness of flesh of tubers, proved to be diverse. A majority of tested cultivars showed favorable response to this treatment. A similar reaction of cultivars to sonication was observed by Sawicka and Dolatowski [2007], Moza et al. [2012] and Aguiar Cipriano et al. [2015].

Ultrasonic processing can change the structure of food materials, which affects the texture, texture and functionality of these products. Many studies have shown that low-intensity pre-ultrasonic treatment improves the texture behavior of vegetable products after heat treatment [Surmacka-Szczęśniak 2002, Adekunte et al. 2010, Terefe et al. 2011, 2014a, 2014b, 2016]. In addition, the use of high-intensity ultrasound improves the consistency, turbidity of the juice and the stability of the turbidity of fruit and vegetable juices [Waldron et al. 1997, Terefe et al. 2014a, 2016, Liu et al. 2017]. The effect observed in the experiment can be attributed to the induction of stress, activation of PME-catalyzed de-esterification of pectin, activation of peroxidase-catalyzed oxidation of proteins of the cell wall structure and phenols by ultrasonically induced production of hydrogen peroxide or a combination of two or more mechanisms. As with other biological and physical stressors, treatment of plant tissue by low-intensity ultrasonic stress can cause defense responses such as oxidative bursts [Wu and Ge 2004, Wu et al. 2008, Terefe et al. 2011] and increased synthesis of secondary metabolites such as phenols [Wu and Lin 2002, 2003]. These effects can in effect lead to the strengthening of plant cell walls by peroxidase catalyzed oxidation of structural proteins of the cell wall and polyphenols and the formation of cross-links.

One of the most important distinguishing features of the sensory quality of potatoes is their consistency after cooking. Shaping the texture of edible boiled potatoes is influenced by many factors, both physiological and climate-soil [Rytel 2004]. However, the most important factors are the potato cultivar and the degree of tuber maturity [Lisińska and Leszczyński 1989, Rytel 2004, Jakubczyk and Uziak 2005]. This is also confirmed by own research. During ripening, the chemical composition of tubers changes and changes occur in the structure and composition of cell walls, in particular the content of dry matter and starch [Lisińska and Leszczyński 1989]. Starch, along with other polysaccharides, belongs to the texture-forming components of the tuber [Rytel 2004, Dolik and Kubiak 2013, Terefe et al. 2014a, 2016].

The sensory properties of potatoes are associated by the consumer with the cultivar however, depending on the degree of tuber maturity, their quality after cooking, and especially the consistency associated with their hardness, can vary significantly, which is confirmed by the research. Strength and compression tests referring directly to properties such as hardness were a very good indicator of mechanical properties [Jakubczyk and Uziak 2005]. The obtained maximum stress values indicated a high hardness of the potato raw material.

Research on raw potato tubers collected at the technical maturity stage (97 on the 100 BBCH scale) showed that their texture varies depending on the variety and the dry matter and starch content in them [Bleinholder et al. 2001]. According to Lisińska and Leszczyński [1989], Rytel [2004], Terefe et al. [2016] the rheological properties of the flesh of potato tubers depend mainly on their protein and water content. The cultivar classification given by Lisińska and Leszczyński [1989] indicates that there is a relationship between the water content of tubers and their texture. The difficulty in rheological research is choosing the right measurement method to obtain full information about the mechanical characteristics of the tested raw material [Surmacka-Szczęśniak 2002, Jakubczyk and Uziak 2005]. Instrumental tests measure various aspects of texture, hence only some of them correlate with selected, characteristic features of given materials. The difficulty in rheological research is choosing the right measurement method to obtain full information about the mechanical characteristics of the tested raw material [Jakubczyk and Uziak 2005].

The study shows that tested traits were also influenced by habitat conditions and the amplitude of the stimulus applied to the tuber flesh. The challenge for the future is therefore the engineering of experimental set designs, in which various mechanical phenomena induced by ultrasounds can be controlled.

CONCLUSIONS

1. The use of ultrasonic energy, that belongs to advanced technology, is innovative and broadens the range of their applications, both in cultivation and potato processing, and affects the stability and physicochemical properties of raw and cooked tubers, which may be crucial for the food industry.

2. Sonication of seed potatoes contributed to reducing the water content in tubers and reducing the acidity of potato juice and increasing the content of starch, improving the texture parameters of raw and cooked tubers, while in boiled tubers – to reduce the total deformation of tubers.

3. Genetic traits of studied cultivars significantly influenced the acidity of potato juice, dry matter content in tubers and rheological properties of raw and cooked tuber flesh:

– cultivar with the highest dry matter content in tubers was medium late ‘Pasja Pomorska’, while the largest parenchyma hydration characterized medium early ‘Nora’, the highest starch content characterized late 'Hinga', and the most appropriate potato juice acidity – medium late 'Baszta';

– minimum hardness of raw tubers characterized 'Rosalind', and cooked – 'Pasja Pomorska'; hardness solids of raw tubers and total work of deformation was the lowest for 'Ursus', suggesting the usefulness of the latter for chips production, the smallest ratio of the deformation work to the hardness, both for raw and cooked tubers, characterized 'Hinga'.

4. Response of studied cultivars towards application of ultrasounds: majority of tested cultivars showed favorable response to this treatment.

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Streszczenie. Celem badań było określenie wpływu sonikacji na właściwości fizykochemiczne sadzeniaków różnych odmian ziemniaka. Do badań wykorzystano próbki bulw z eksperymentu polowego przeprowadzonego w Parczewie (51°38'N, 22°54'E) w latach 2015–2017. Eksperyment polowy przeprowadzono metodą podbloków losowanych, w układzie zależnym, split-plot. Czynnikiem pierwszego rzędu były zabiegi przedsadzeniowe: 1) zastosowanie ultradźwięków, 2) obiekt kontrolny, bez stosowania ultradźwięków. Czynnik drugiego rzędu stanowiło 10 odmian ziemniaka, ze wszystkich grupy wczesności. Materiał sadzeniakowy poddano sonikacji zanurzeniowej za pomocą urządzenia ultradźwiękowego, wannowego. Oceniono następujące parametry: suchą masę bulw, zawartość skrobi, cechy tekstury miąższu surowego i gotowanego bulw oraz kwasowość soku ziemniaczanego. Sonikacja przyczyniła się do wzrostu zawartości suchej masy i skrobi w bulwach, zmiany pH soku w kierunku reakcji alkalicznej oraz zwiększenia parametrów teksturalnych bulw surowych i gotowanych.

Słowa kluczowe: kwasowość, sucha masa bulw, skrobia, tekstura, ultradźwięki, ziemniak

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