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TRANSFER OF MICROWAVE IRRADIATION EFFECTS OF SEED POTATOES (*SOLANUM TUBEROSUM* L.) TO THE PLANTS OF NEXT GENERATIONS

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Abstract

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The purpose of the research was to determine whether the effects of irradiation of seed potatoes, resulting in an increased total tuber yield, are transferred to the plants of next generations. The research was conducted between 2011 and 2013 in southern Poland on very early edible potato varieties, Bard, Flaming and Orlik. The transfer of irradiation effects to the plants of next generations was not confirmed. The highest yield was recorded in the first year of the experiment on crops grown from microwave-irradiated seed potatoes. No significant effect of microwaves on the potato yield in the next years was noted.

Key words: potato, microwave, yield, genotype

List of abbreviations: f – microwave frequency (Hz); ε_0 – permittivity of free space (F·m^{-1}); ρ_B – potato tuber density (kg·m^{-3}); ε''_B – coefficient of dielectric losses of potato tuber (-); E_B – intensity of electric field generated in the seed potato by microwaves (V·m^{-1}); m_B – seed potato mass (kg); P_B – power induced in the seed potato (W); S_d – standard deviation; W_z – coefficient of variation (%); min., max., av. – respectively, minimum, maximum and average value

Introduction

The paper summarizes the results of an agricultural physics experiment which lasted a few years and intended to determine the effects of microwave radiation on the plants of potato *Solanum tuberosum* L. The experiment was multi-range in character and comprised examination of the above-ground part of potato, potato yield-related features and storage of tubers. The paper presents only the results of the research concerning the effects of microwaves on the potato total yield (mass of potato tubers).

The results of the research by Monneveux et al. (2013) indicate that the approaching climatic changes may reduce the potato yield. At the same time, according to Błaszczak et al. (2005) the presence of pathogens in the seed potatoes is one of the most important factors affecting the yield losses in potato crops. It should be emphasized that, despite the growing consumption of cereal products (groats, rice), potatoes remain one of the main foodstuffs and food-processing materials (Head, 2011). New agrotechnical methods must be sought in order to keep the potato yield at the level which satisfies the demand of consumers and food processing industry. Such methods should be applied in accordance with general environmental protection rules and in addition they should conform to the standards for ecological farming. Physical methods of refining of the seed material have been developed as an alternative to chemicalization of crops. Refining of the seed material should not only increase its vigour and reduce the variability of physical and chemical properties, but also should have a beneficial effect on the growth and development of plants even in the next generation (Wójcik et al., 2004). Microwave irradiation of seed potatoes is one of the methods of physical stimulation of seed material (Olchowik et al., 2002).

The world scientific literature reported the results of research on the positive impact of microwaves on seeds: len-

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tils (Aladjadjiyan, 2010), bean (Tylkowska et al., 2010), rape (Oprică, 2008), soybean, wheat, barley and oats (Reddy et al.,1995, 1998; Yoshida et al., 2000; Ponomarev et al., 1996). In connection with potato tubes, the microwave radiation has been most frequently used in the starch research or the polymer technology (Lu et al., 2012; Liu et al., 2012; Staroszczyk et al., 2013) or in the food technology (Seyhun, 2009; Lyng, 2014). The research on effects of physical methods on potato (*Solanum tuberosum* L.) has been conducted at the Unit of Agricultural and Food Production of the Agricultural University in Krakow, Poland since 2002. The research comprises mainly the experiments associated with influence of magnetic and electric fields and microwave radiation on the potato tubers (Marks et al., 2005, 2008, 2010). The results clearly indicate that such physical methods can modify some processes of the potato ontogenesis. Microwave radiation was applied on the tubers of the following potato varieties: Felka Bona, Rosara, Velox and Lord. Irradiation of seed potatoes resulted in statistically significant increase of total potato yield (Jakubowski, 2010a,b) and irradiation before storage reduced the infestation by *Rhizoctonia solani* Kühn (Jakubowski, 2010c).

According to the methodology of the above-mentioned experiments, potato tubers (new seed material) were irradiated every year before planting or storage (Rivera et al., 2012). Such methodological approach allows obtaining information on effects of a given method on the tested material only in one vegetation or storage period. This paper is an attempt to complement the characteristics of the physical method comprising the microwave irradiation of the tubers with information on possible retaining by the potato plant of the modifications (increased yield) caused by irradiation. From the economic point of view, the retaining of such modification would be beneficial for the agricultural practice (Rivera et al., 2012). The aim was to verify whether the effects of irradiation of potato tubers which increased the total yield can be passed on to the next generations.

Scope and Methods of Research

The working assumption has been that microwave radiation will significantly affect the total potato yield during all years of the research. Therefore, the following parametric definition of significance was formulated:

- H_0 – there is no significant difference between the median values of yield weight from irradiated potato seeds and from the control samples
- H_1 – there is a significant difference between the median values of yield weight from irradiated potato seeds and from the control samples

The research was conducted between 2011 and 2013 in southern Poland. The experimental plots were located on light soil, slightly loamy sand, soil quality class IIIa (according to the agricultural suitability classified as "good mountain soil"). In order to achieve the projected goal of the research, the seed potatoes were microwave irradiated only in the first year of the experiment and then planted. The seed material in the first year of the experiment (2011) was certified seed potatoes (C_A) of the first multiplication (which means that according to the Commission Implementing Directive 2014/20/EU/ of 6 February 2014 determining Union grades of seed potatoes this material can be considered basic). In 2012 the seed material used in the experiment was from the potatoes grown in the previous year (2011) from the microwave-irradiated seed potatoes, and in 2013 the seed potatoes were the material from 2012. The experiment was conducted on very early varieties of edible potato, Bard, Flaming and Orlik. The selection of varieties was determined by the following reasons (order according to the weight of the feature): permitted number of internal multiplications, agrotechnical and fertilization requirements, time limit for achieving the full technical maturity of the tubers which qualifies them for harvesting. The experiment was conducted in three repetitions (each with three replications) in order to eliminate the impact of soil and climatic conditions. The repetitions were about 20 km apart. It was assumed that the reaction of potato plants to the microwave radiation would be similar within each repetition. The effect of microwave irradiation of seed potatoes was examined on control plants (control sample for individual varieties was assigned to each replication).

The combinations of the experiment in the repetition were placed in the completely randomized design. The scope of the experiment encompassed both the laboratory works (irradiation of seed potatoes and determination of the yield mass from a single plant) and the field works (agrotechnology, *in situ* observation of plants). The mass of the potato tubers was determined with a precision balance (precision 0.1 g). The scope also included soil analyses (richness of soil) and determination of weather conditions in the experiment area (precipitation and temperature values were obtained from a weather station of Institute of Meteorology and Water Management located 15 km away from the nearest repetition). The richness of soil was determined according to the following standards: pH in KCl - PN-ISO 10390 1997, P_2O_5 - PN-R-04023 1996, K_2O - PN-R-04022 1996, Mg - PN-R-04020 1994. The soil richness was evaluated according to the recommendations of Soil Cultivation and Fertilization Institute. The same arrangement and type of agrotechnical operations was applied in all repetitions (Tables 1 and 2).

Table 1
Chemical analysis of soil samples in individual repetitions (data from 2010)

Number of repetition	Agronomic soil category	Acidity		Liming	The content of digestible ingredients [in mg per 100 g of soil] and evaluation		
		pH (in KCl)	reaction		P_2O_5	K_2O	Mg
1		5.8			14.1 (average)	15.8 (average)	8.4 (high)
2	average	6.2	slightly acidic	unnecessary	9.4 (low)	12.1 (low)	6.5 (average)
3		6.4			15.2 (high)	20.2 (high)	5.5 (average)

Table 2
Average precipitation and air temperature during the vegetation period (April – August)

Year	Precipitation, mm	Temperature, °C
2011	419	13.6
2012	455	15.1
2013	391	14.3
	average = 421.7	average = 14.3

The seed potatoes were irradiated using the 2.45 GHz microwave generator (Figure 1). A single seed potato was microwave irradiated for 10 s at the constant generator power of 100 W. The generator operating parameters were chosen on the basis of the author's own research (Jakubowski, 2010a,b,c). To be microwave irradiated, the potato tuber (9) was placed in the generator chamber (6). The device was equipped with a very accurate time switch (1). The generator's principal component was a magnetron (2) consisting of the anode block (3) with vacuum cavities which number and shape entailed a desired characteristics of the vacuum tube (Dvurechenskaya et al., 2010; Ziaja et al., 2010). The anode was placed between the poles of a strong magnet (4) which curved the trajectories of the electrons emitted by the incandescent cathode (5). Electrical vibration induced in the cavities changed the formed cloud of electrons into an electromagnetic standing wave, and the electrons in the cavities gave their energy away (in the form of microwaves) in the electrical field of the cavities. The microwaves were transported through a waveguide (8) to the interior of a hermetic chamber (which performed the function of a Faraday cage) equipped with a rotating bottom (7). The mass of tubers from one plant was determined using a laboratory scale (1 g measurement accuracy).

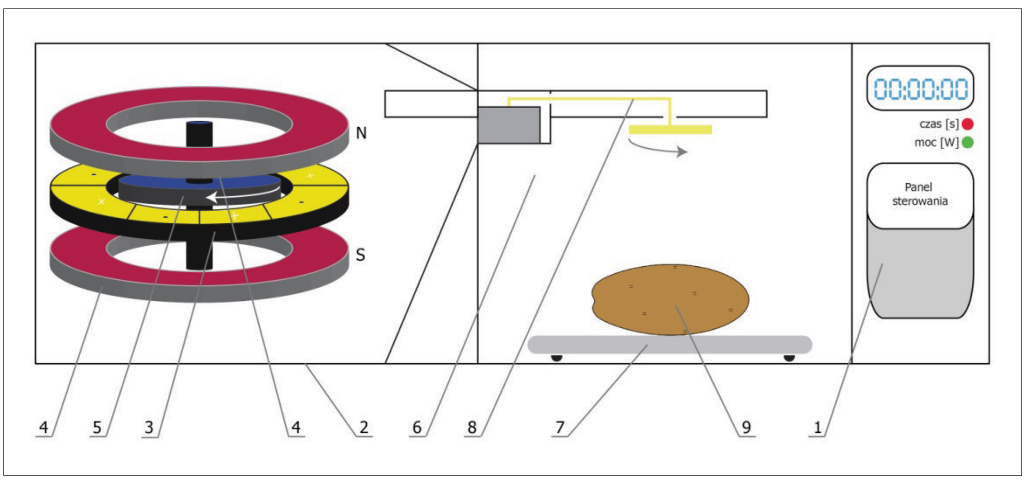

Fig. 1. Layout of the stand for microwave irradiation of potato tubers (description of the figure is in the text)

The following formula was used to estimate the energy of microwaves absorbed by a seed potato during the irradiation (1) (Jakubowski, 2011):

$$P_B = 2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot (E_B)^2 \cdot (\frac{m_B}{\rho_B}) \cdot \varepsilon''_B \qquad (1)$$

The statistical analysis was performed using the *STATISTICA 10* package with the assumed significance level of α = 0.05. The minimum number of plants necessary to achieve the goal of the research was determined. The minimum sample size was determined using the *t*-test for a single sample. With the mean values of the population and standard deviation known from pilot experiments (Jakubowski, 2010a,b), the power of test was assumed at 0.9 and the probability of type I error at α = 0.05. The conformity of empirical distribution to the theoretical (normal) distribution was determined using the Shapiro-Wilk test. The variance homogeneity was examined using the Levene test. The multi-factor analysis of variance for factor effects was used. In order to solve the scientific problem, the statistical analysis focused on the effects of interaction between the grouping variables (year, irradiation, and then repetition and variety) and their influence on the dependent variable (yield mass). The impact of statistically significant quality predictors was examined with the post-hoc test using the T Tukey HSD multiple comparisons procedure.

Results

The mass of seed potatoes (Table 3) used in the experiment ranged from 29.2 to 45.9 g (coefficient of variation in the 12.4-29.0% range) which means that as a result of exposure they absorbed about 1.01-1.14 W of microwave energy (absorbed power).

The Shapiro-Wilk test showed conformity of the empirical distribution with the normal distribution. The Levene test confirmed the variance homogeneity in the tested samples. This sanctioned the application of multi-factor analysis of variance with allowance for the interaction effects. The results of analysis of variance (Table 4) clearly indicate that during the three-year experiment period the microwave radiation did not have an impact on the potato tubers yield. At the same time, the potato tubers yield was different in individual years (Table 5), the difference being that the yield was greater in the year in which the seed material was irradiated than in subsequent years.

Such results cannot be explained by the degeneration process of seed potatoes because the certified and basic seed material was used in the experiment. The results should be explained on one hand by cessation of the microwave action on the seed potatoes (in the second and third year of the experiment) and on the other hand by the influence of accidental external factors not accounted for in the experiment. This assumption should however take into account a possibility that the potato plants could be under the influence of irradiation during the experiment duration, but this effect was eliminated by external factors. The mathematical and numerical substantiation of such situation is two values from Table 4: statistically significant free term (taking into account the model approach for the analysis of variance) and random experiment error with normal distribution (with mean equal to zero and known variance). Such result of the

Table 3
Mass of seed potatoes and absorbed power during the microwave irradiation

Year	Number of repetition	Mass of seed potatoes, g			Basic statistics		P_B (W)
		min.	max.	av.	S_d, g	W_z, %	
2011	1	29.2	41.3	35.2	8.6	24.3	1.01
	2	31.5	41.7	36.6	7.2	19.7	1.05
	3	30.9	39.1	35.0	5.8	16.6	1.00
2012	1	30.1	44.2	37.1	10.0	26.9	1.06
	2	33.2	39.6	36.4	4.5	12.4	1.04
	3	31.8	40.8	36.3	6.4	17.5	1.04
2013	1	30.1	39.7	34.9	6.8	19.5	1.00
	2	29.8	45.2	37.5	10.9	29.0	1.08
	3	33.7	45.9	39.8	8.6	21.7	1.14

Table 4
Results of analysis of variance taking into account the influence of independent variables used in the experiment on the yield of potato tubers

Independent variables	Sum of squares	Number degrees of freedom	Mean square	Value of F test	Value of test probabilisty
Free word	629.37	1	629.3701	155224.4	0.0000
Year of studies (1)	4.4376	2	2.2188	547.2	0.0000
Repetition (2)	3.3615	2	1.6808	414.5	0.0000
Variety (3)	0.0279	2	0.0140	3.4	0.0327
Microwave radiation (4)	0.0082	1	0.0082	2.0	0.1565
1*2	13.0883	4	3.2721	807.0	0.0000
1*3	0.2760	4	0.0690	17.0	0.0000
2*3	0.1565	4	0.0391	9.7	0.0000
1*4	0.2833	2	0.1417	34.9	0.0000
2* 4	0.1313	2	0.0657	16.2	0.0000
3*4	0.0340	2	0.0170	4.2	0.0157
1*2*3	0.2866	8	0.0358	8.8	0.0000
1*2*4	0.1982	4	0.0495	12.2	0.0000
1*3*4	0.2095	4	0.0524	12.9	0.0000
2*3*4	0.1923	4	0.0481	11.9	0.0000
1*2*3*4	0.2004	8	0.0250	6.2	0.0000
Error	1.9705	5346	0.0003		

Table 5
Arrangement of homogenous groups taking into account the impact of the year of the experiment on the yield of potato tubers

Year of studies	Yield mass from a single plant, kg	Homogenous groups		
		1	2	3
2013	0.97	****		
2012	1.07		****	
2011	1.15			****

experiment was a reason to conduct the post-hoc tests for effects of interaction between the years of experiment and the influence of microwave irradiation on the yield mass. The multiple comparisons proved the existence of four homogenous groups which arrangement indicates that the microwave radiation modified the yield of potato tubers only in the first year of the experiment that is in the year in which the plants grew from seed potatoes directly subjected to microwaves (Table 6).

Such arrangement of homogenous groups does not allow to state that the effect of irradiation of potato seeds, as shown by the yield mass, can be transferred to the plants of next generations. At this stage of the experiment one should assume that the changes caused by microwaves which manifest themselves by the potato yield in the first year of the experiment do not modify the genotype which conditions the inheritance properties of the plant. This result also leads to the conclusion that only the irradiation of seed potatoes directly before planting them can affect the yield of potato tubers. Higher yield in the first year of the experiment of potatoes grown from previously microwave-irradiated seed material was expected. In previous research (concerning the impact of physical methods on the potato plants) such effect was explained by thermal and athermal action of microwave radiation on seed potatoes. The microwaves penetrating the seed potato cause oscillation of ions in the electrolytes and of molecules in polarized dielectrics (Banik et al., 2003), as a result of which the waterlogged tuber can become heated. According to Devyatkov (1987), a thermal effect takes place when as a result of absorption of electromagnetic radiation energy the object temperature increases by more than 0.2°C. The thermal effects depend also on the ratio of the size of the irradiated object to the wavelength and the object placement in relation to the direction of magnetic field vector. Jethon et al. (2000) claim that microwaves can cause changes in the organisms' adaptation systems and the effects on these systems can include bioelectric, metabolic and structural changes on

Table 6
Arrangement of homogenous groups taking into account the impact of interactions between the years of the experiment on the yield of potato tubers

Year of studies	Microwave radiation	Yield mass from a single plant, kg	Homogenous groups			
			1	2	3	4
2013	yes	0.95				****
2013	not[X]	0.98				****
2012	not[X]	1.05			****	
2012	yes	1.07			****	
2011	not[X]	1.13		****		
2011	yes	1.18	****			

[X] control sample

the cellular and subcellular level. If a thermal effect is not stressogenic to the plant (e.g. does not cause denaturation of protein structures or damage of cell membrane), then it can be beneficial to the plant by accelerating the biochemical transformations, it can have an impact on the metabolism and can result in e.g. an increased yield.

The results of experiments by Belaev et al. (1996), Grundler (1992) and Devyatkov et al. (1991) indicate that the microwave radiation affects many life processes also when the field intensity is significantly below the lower limit of thermal effect. In case of biological processes, the relationship between the reaction speed and temperature is determined according to the Arrhenius equation and the van't Hoff rule. It should be emphasized that, in addition to the concentration of substrates, redox potential, osmotic pressure or presence of inhibitors and activators, temperature is a significant factor affecting the speed of biochemical transformations (Willers et al., 1993). A higher temperature means an increase of the particles' speed augments the frequency of particles' collisions and hastens the enzymatic reactions. Stimulation of biochemical processes by microwaves can enhance the growth of the above-ground part of the plant, and as a result increase its yield. The growth of the above-ground part is explained by a greater number of actively germinating buds in the irradiated potato. Marks et al. (2003) claim that the plants grown from the seed potatoes of the Irga variety microwave-irradiated before storage showed earlier emergence. Similarly, the stimulation of the Vineta seed potatoes by a variable magnetic field had a beneficial effect on the vegetation of the above-ground part of the plant (Marks et al., 2010). The author's research (Jakubowski, 2008) on the growth dynamics of the Felka Bona potato germs showed that the microwave-irradiated seed potatoes had larger mass and number of germs.

A so-called "overlap" of the groups was noted in case of results presented in Table 6 (meaning that all average values belonging to various groups will be significantly different). In that case, the approximate probability values for the Tukey HSD test (Table 8) were additionally determined for the impact of the interaction between the potato varieties the microwave irradiation. Based on the results from Tables 7 and 8, it is impossible to infer about the impact of microwaves on the yield of potato varieties used in the experiment. The varieties' yield was even, and the only yield differences were between the Bard and Orlik varieties (Bard has the highest yield per hectare of all potato varieties used in the experiment). The results presented in Table 9 indicate that the same potato varieties had different yields within individual repetitions. Each repetition made up a separate homogenous group (an exception being Flaming which made up a separate homogenous group in the third repetition and had the yield 3.6% higher than the Bard variety growing in the same repetition). It should be assumed that the weather conditions were the same as the locations of the repetitions were close to each other. The agrotechnical operations were also identical in each repetition (in some cases their dates differed by 3-4 days). The soil richness tests showed a diverse content of individual macroelements (Table 1). In comparison with other repetitions, the soil in the repetition No 3 had a high content of potassium and phosphorus (an analogous situation occurred in case of repetition 1 in relation to 2). These macroelements have a decisive impact on the action of enzymes which determine the physiological processes associated with the potato growth phases (e.g. bud formation, tuberization, and maturation of tubers). In the opinion of the author, the research on the effects of microwaves on the potato plants should continue. It is advisable to learn more about the mechanisms of the presented physi-

Table 7
Arrangement of homogenous groups taking into account the impact of interactions between the potato variety and the microwave radiation on the yield of potato tubers

Variety	Microwave radiation	Yield mass from a single plant, kg	Homogenous groups	
			1	2
Orlik	not[X]	1.06	****	
Bard	not[X]	1.07	****	****
Orlik	yes	1.07	****	****
Flaming	yes	1.08	****	****
Flaming	not[X]	1.09	****	****
Bard	yes	1.10		****

[X] control sample

cal method which area of application can be wider. Assuming however that microwave irradiation of the tubers acts on the tuber structure on the cellular or subcellular level, it is recommended to use more accurate research tools from the fields of molecular biology or genetics.

Conclusions

The results of the experiment do not indicate that the effect of microwave irradiation of seed potatoes, resulting in an increased total tuber yield, is transferred to the plants of next generations.

- The highest yield was noted in the first year of the experiment among the potato plants grown from the microwave-irradiated seed potatoes.

Table 8
Approximate probability values for the post-hoc tests – impact of interactions between the potato variety and the microwave radiation on the yield of potato tubers

Variety	Microwave radiation	{1} - 1,10	{2} - 1,07	{3} - 1,07	{4} - 1,06	{5} - 1,08	{6} - 1,09
{1} Bard	yes		0.0656	0.0942	**0.0037**	0.1611	0.8968
{2} Bard	not[X]	0.0656		0.9999	0.9484	0.9991	0.5380
{3} Orlik	yes	0.0942	0.999993		0.9074	0.9999	0.6307
{4} Orlik	not[X]	**0.0037**	0.948414	0.9074		0.8077	0.1013
{5} Flaming	yes	0.1611	0.999151	0.9999	0.8077		0.7712
{6} Flaming	not[X]	0.8968	0.538035	0.6306	0.1013	0.7712	

bold font - the value of statistically significant, [X] control sample

Table 9
Arrangement of homogenous groups taking into account the impact of interactions between the potato variety and the experiment location on the yield of potato tubers

Number of repetition	Variety	Yield mass from a single plant, kg	Homogenous groups			
			1	2	3	4
2	Orlik	0.98	****			
2	Flaming	0.97	****			
2	Bard	1.00	****			
1	Flaming	1.06		****		
1	Bard	1.09		****		
1	Orlik	1.09		****		
3	Orlik	1.15			****	
3	Bard	1.17			****	
3	Flaming	1.21				****

- Disproportions between the yields of potato varieties in individual repetitions were caused by varying content of absorbable forms of phosphorus and potassium in soil.

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