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Comparison of the growth of royal paulownia strains (*Paulownia tomentosa* Steud.) suitable for biomass production under stressful conditions

Porównanie wzrostu klonów paulowni puszystej (*Paulownia tomentosa* Steud.) przydatnych do produkcji biomasy w warunkach stresowych

Abstract. The aim of the present study was to estimate the growth and winterhardiness of thirteen strains of royal paulownia in south-east Poland. Paulownia plants were grown under stressful conditions, such as poor soil, high density, no mineral fertilisation and no irrigation. However, intensive plant growth was confirmed in the first two years of vegetation. Among the studied strains, the 'LuP', 'LuD' and 'We' strains showed high growth intensity, high yield potential and the highest winter survival. They also had a significantly higher SPAD index than others. The selected strains were probably more tolerant of abiotic stress. Some specimens showed even stronger growth. The fast-growing selected paulownia strains could give an estimated 1.8 t ha^{-1} of fresh and 0.4 t ha^{-1} of dry shoot biomass. The leaves of paulownia plants are also a valuable source of biomass. Therefore, the aboveground biomass yield could be double that previously estimated.

Keywords: quotient method, short-rotation plantation, SPAD index, winterhardiness, woody biomass

INTRODUCTION

Royal paulownia (*Paulownia tomentosa* Steud.) is a deciduous tree native to China [Zhu et al. 1986, Woods 2008]. This species was introduced to North America, Australia and Western and Southern Europe [Essl 2007, Yadav et al. 2013]. Paulownia is one of the

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fastest-growing trees in the world [Icka et al. 2016]. In favourable conditions, the annual growth of paulownia plants can reach up to 5 m in length [Zhu et al. 1986].

Paulownia trees are widely used. The fast growth rate, high biomass production and resprouting potential make it a valuable plant in the energy industry. These plants have a higher biomass production than other woody crops used for energy purposes [López et al. 2012, Zuazo et al. 2013]. The annual biomass production can reach from 50 to 150 t ha^{-1} [Azzarello et al. 2012, López et al. 2012]. Under favourable conditions, 5–7-year-old plantation of 2000 trees per hectare can yield up to 150–300 tons of wood annually [Azzarello et al. 2012, Yadav et al. 2013]. Biomass from the paulownia plantation can be harvested in two- or three-year cycles for 20–25 years. After shoot harvest, plants are regenerated from the existing root systems and shoot remains without replanting [Danciu et al. 2016]. Thus, paulownia is a desirable species for biomass production in the world.

Paulownia wood can be used for making furniture, house construction, shipbuilding, farm implements, handicrafts, toys, packing boxes, musical instruments and the pulp and paper industry [Ayan et al. 2006, Akyildiz and Kol 2010]. Due to their high tolerance to heavy metals and fast growth rate, these plants are used for phytoremediation [Doumett et al. 2008, Stankovic et al. 2009, Wang et al. 2010]. Paulownia leaves are also used as green fertiliser or animal feed [Woźniak et al. 2018, Al-Sagheer et al. 2019]. The empress tree can also have medicinal, ornamental or beekeeping purposes [Zhu et al. 1986, Icka et al. 2016].

Recently, the ‘Oxytree’ (*P. fortunei* × *P. elongata*) and ‘Shan Tong’ (*P. tomentosa* × *P. fortunei*) hybrids have been widely cultivated in Poland [Lisowski and Porwisiak 2017, Lisowski and Porwisiak 2018, Liszewski and Bąbelewski 2018a, 2018b]. However, their cultivation may be risky as such genotypes are interspecific hybrids with *P. fortunei*. This species is not considered winter-hardy, as it tolerates temperatures as low as –10°C [Zhu et al. 1986]. It seems that *P. tomentosa* genotypes, the most winter-hardy species from the *Paulownia* genus, should be used first-line in Poland. Royal paulownia tolerates frost conditions below –20°C [Woods 2008].

Paulownia species are cultivated in the warmer parts of the world [Yadav et al. 2013]. Almost nothing is known about the possibility of their cultivation in regions with moderate and cold climate zones, such as Poland. Therefore, the aim of the present study was to estimate the growth and winterhardiness of thirteen strains of royal paulownia in the first two years of vegetation in Polish climatic conditions.

MATERIAL AND METHODS

The field experiment was established in south-eastern Poland, in Grochowe near Mielec (50°21'N 21°29'E) on sandy soil belonging to the VI quality class. The soil pH was acidic with medium phosphorus, low potassium and high magnesium content (tab. 1). The microelement content was generally low. Similarly, the content of organic matter and total nitrogen was also low. Temperature and precipitation data were from the Meteorological Station of the University of Rzeszów (tab. 2). In 2014 and 2015, the monthly temperatures were higher than the long-term average. However, in these years, the total precipitation was definitely below the long-term average. In particular, June and August 2015 were drier and warmer than in previous years.

Table 1. Soil chemical properties before the start of the experiment

pH_{KCl}	P_2O_5	K_2O	Mg	B	Mn	Cu	Zn	Fe	Nitrogen	Organic matter
	(mg·kg^{-1} of soil)			(mg·kg^{-1} of soil)					g·kg^{-1}	g·kg^{-1}
6.0	141	50	72	1.0	30.9	4.6	17.9	898	1.2	20.5

Table 2. Comparison of weather conditions in Rzeszów

Year	Month												Annual	Vegeta-tion
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII		
temperature (°C)													average (°C)	
2014	0.5	3.3	6.8	10.1	14.2	16.3	20.1	18.0	15.3	9.7	6.6	1.8	10.2	17.4
2015	1.0	1.6	4.8	8.6	13.0	17.5	19.9	21.4	15.4	7.5	5.4	3.3	10.0	17.7
1981–2010	–2.3	–1.3	2.8	8.5	14.0	16.8	18.8	18.1	13.5	8.6	3.4	–1.0	8.4	16.2
precipitation (mm)													sum (mm)	
2014	19.7	16.9	37.8	29.9	92.2	48.1	57.1	46.8	32.2	24.0	9.2	12.5	426.1	275.2
2015	28.0	10.3	37.9	25.7	85.1	8.8	52.3	6.0	48.6	36.9	46.9	8.5	394.8	195.9
1981–2010	30.5	29.0	36.7	46.7	81.4	82.6	90.7	68.5	69.3	42.6	37.1	37.5	652.6	392.5

The studies were conducted on generatively propagated royal paulownia plants. Most of the strains came from seeds obtained from several-decade-old paulownia trees growing in botanical gardens, arboretums or private property in Poland (tab. 3). The three strains were of foreign origin. In June 2014, ten-week-old *Paulownia* seedlings with uniform growth were planted in the ground. These plants reached a height of approximately 15 cm. A randomized complete block design in four replications was established. Forty plants represented each strain. Paulownia plants were planted in double-row plots with a spacing of 0.75 m between rows and 3 m between bands. Each plant was spaced in a row 0.5 m apart. Thus, the plant density was approximately 10.000 plants ha^{-1}. The sewage sludge at 80 t ha^{-1} was used in the soil before planting the plants. The sludge sample had an alkaline pH, and contained approximately 58.8% organic matter, 5.9% total nitrogen, 1.3% ammonium nitrogen, 3.5% phosphorus, 3.8% calcium and 0.8% magnesium of dry matter and low heavy metal concentration. In 2015, no fertiliser was applied to the plants.

The biometric and physiological measurements were made in 2014–2015. In September, one fully expanded leaf from each plant was selected. The size of the leaf blade and petiole, and their fresh and dry mass, were determined. The relative chlorophyll content expressed in SPAD units was measured using a Chlorophyll Meter SPAD-502Plus. After the end of the vegetation period, the following biometric measurements, such as the length and base diameter of the strongest shoot, total length and number of shoots, were determined. After the winter period, the real winterhardiness of plants was assessed by determining the number of dead plants. The fresh and dry shoot mass was also determined.

Statistical analysis was performed using Statistica v.13.1. Collected data were subjected to an ANOVA, $LSD_{0.05}$ test. Ward's method and Euclidean distance were used to evaluate the similarity of the studied paulownia strains. All statistical tests were considered significant at the $p = 0.05$. Then, the best paulownia strains were selected using the quotient method according to Paszkowska and Mazurkiewicz [1967] and Kuraczyk et al. [2003]. This method divides the average value of a trait for a strain by the average value of this trait for all strains. The sum of the quotients determines the strain index.

Table 3. The origin of studied paulownia strains

Symbol	Locality	The origin of the seeds
Bd	Bydgoszcz, Poland	Plant Breeding and Acclimatization Institute in Radzików Bydgoszcz Research Center
Bg	Boguchwała, Poland	private property
Bl	Bolestraszyce, Poland	Arboretum in Bolestraszyce
Cr	Crimea	unknown
Kr	Kraków, Poland	Botanic Garden of the Jagiellonian University
LuB	Lublin, Poland	Botanic Garden of the University in Lublin
LuD	Lublin, Poland	Botanic Garden of the University in Lublin
LuP	Lublin, Poland	private property
Po	Poznań, Poland	Botanic Garden of the University in Poznań
Ru	Romania	University Campus in Oradea
Wa	Warszawa, Poland	Botanic Garden of the University of Warsaw
We	Hungary	unknown, Florpak seed company
Wr	Wrocław, Poland	Botanic Garden of the University of Wroclaw

RESULTS AND DISCUSSION

Paulownia is one of the fastest-growing trees in the world [Woods 2008, Icka et al. 2016]. However, information about the intensive growth of these plants comes mainly from warmer climate zones [e.g. Ulu et al. 2002, Bergmann 2003, Stankova et al. 2016]. There is limited information on the growth of royal paulownia in Polish climatic conditions. Nevertheless, preliminary observations and results on the growth of 'Shan Tong' and 'Oxytree' in western and central Poland are available. In Murowana Goślina near Poznań, the fertilised plants had an average of 0.7 m in height and 1.3 cm in diameter in the first year of vegetation [Smarul et al. 2018]. In turn, unfertilised plants were 0.5 m in height and 0.7 cm in diameter. Similarly, Kadlec et al. [2023] recorded a growth of paulownia by 0.5–0.8 m after the first year in the Czech Republic. In Poland, field experiments were also established in Łomża and Wrocław. The 'Oxytree' plants had an average of about 1 m in height and 2.8 cm in diameter after four months of vegetation [Lisowski and Porwisiak 2017, Liszewski and Bąbelewski 2018a]. However, the paulownia plants were grown in optimal conditions, such as lower density (625 plants ha^{-1}), mineral fertilization before sowing and top dressing, and irrigation during the vegetation period. The optimal conditions for the growth of paulownia plants are sandy soil, with a groundwater level below 1.5–2 m and pH 6.5–7.5. The optimal temperatures for maximum growth are 24–30°C and precipitation is 760 to 1200 mm annually [Woods 2008]. In our study, despite poor soil fertility and water scarcity, intensive growth of royal paulownia was also confirmed. After four months of vegetation, the average length of the strongest shoot surpassed 0.5 m, whereas the diameter of the shoot base was 1.7 cm. Significant differences were found among the studied paulownia strains (tab. 4). The 'LuP' and 'We' strains grew more intensively than the others. Their shoot length was close to 0.7 m, whereas the stem base diameter was almost 2 cm. The shoots of the strongest specimens were longer and thicker, exceeding 1.1 m in length and 2.5 cm in base diameter. In the year of planting, the plants generally exhibited strong apical dominance.

Table 4. Biometric properties of shoots of studied paulownia strains after the first year of vegetation

Strain	Length of the strongest shoot (m)		Total length of shoots per plant (m)		Number of shoots per plant		Diameter of shoot base (cm)	
	$\bar{x}$	max	$\bar{x}$	max	$\bar{x}$	max	$\bar{x}$	max
Bd	0.47^{a}	0.67	0.53^{a}	1.01	1.2^{ab}	3.0	1.5^{a}	2.1
Bg	0.56^{cde}	0.85	0.67^{bc}	2.13	1.3^{b}	5.0	1.6^{ab}	2.3
Bl	0.54^{bcd}	0.87	0.58^{ab}	1.35	1.1^{ab}	3.0	1.6^{abc}	2.1
Cr	0.57^{de}	0.84	0.58^{ab}	0.84	1.0^{a}	2.0	1.8^{cd}	2.4
Kr	0.54^{bcd}	0.76	0.56^{a}	1.10	1.1^{a}	2.0	1.7^{bcd}	2.3
LuB	0.48^{ab}	0.75	0.67^{bc}	1.54	1.5^{c}	3.0	1.7^{bcd}	2.6
LuD	0.56^{cde}	0.81	0.63^{abc}	1.35	1.2^{ab}	4.0	1.8^{de}	2.7
LuP	0.63^{fg}	0.92	0.84^{d}	2.08	1.5^{c}	4.0	1.8^{de}	2.5
Po	0.57^{de}	0.81	0.58^{ab}	1.02	1.0^{a}	2.0	1.7^{bcd}	2.3
Ru	0.54^{cd}	0.80	0.58^{ab}	0.87	1.1^{ab}	3.0	1.7^{bcd}	2.2
Wa	0.61^{ef}	0.91	0.61^{abc}	0.91	1.0^{a}	1.0	1.8^{de}	2.4
We	0.67^{g}	1.16	0.70^{c}	1.34	1.1^{a}	2.0	1.9^{e}	2.5
Wr	0.50^{abc}	0.72	0.53^{a}	1.28	1.1^{ab}	3.0	1.7^{bc}	2.1
Mean	0.56	–	0.62	–	1.2	–	1.7	–

$\bar{x}$ – average forstrain; max – maximum value for specimens; different letters indicate significant differences among means at $p = 0.05$

Fig. 1. Differences in the growth of paulownia strains in the second year of vegetation (Grochowe in July 2015)

Summer 2015 was generally drier than average. June and August, which are most significant for paulownia growth, were extremely dry. After the second year of vegetation, the unfertilised plants had an average of 0.7 m in height and 1.5 cm in diameter. Among all tested strains, the ‘LuP’ and ‘LuD’ grew more intensively (tab. 5, fig. 1). The specimens of ‘LuP’ were almost 1.5 m in height and 3 cm in diameter. The total length of shoots per plant surpassed 4.6 m. Better results were obtained by Lisowski and Porwisiak [2018] and Liszewski and Bąbelewski [2018b] on the ‘Oxytree’ plantation. In Łomża, the two-year-old plants averaged 2.1 m in height and almost 6 cm in diameter. In Wrocław, the average height of the two-year-old plants was approximately 2.8 m, and their diameter was 5.9 cm. It is worth emphasising that these plants were grown under low plant density, irrigation and fertilisation.

Table 5. Biometric properties of shoots of studied paulownia strains after second year of vegetation

Strain	Length of the strongest shoot (m)		Total length of shoots per plant (m)		Number of shoots per plant		Diameter of shoot base (cm)	
	$\bar{x}$	max	$\bar{x}$	max	$\bar{x}$	max	$\bar{x}$	max
Bd	0.54[a]	1.05	0.77[a]	1.70	1.8[a]	4.0	1.4[a]	2.5
Bg	0.68[bc]	1.08	1.04[ab]	1.91	1.9[ab]	3.0	1.5[ab]	2.2
Bl	0.62[ab]	1.12	0.90[ab]	1.82	1.8[a]	5.0	1.5[a]	2.6
Cr	0.73[bc]	1.11	1.57[c]	3.74	2.7[de]	5.0	1.6[ab]	2.3
Kr	0.70[bc]	1.07	1.11[ab]	2.06	1.8[a]	4.0	1.6[ab]	2.2
LuB	0.69[bc]	1.07	1.54[c]	3.64	3.2[e]	7.0	1.6[ab]	2.4
LuD	0.79[cd]	1.48	1.52[c]	3.80	2.4[bcd]	5.0	1.7[b]	2.9
LuP	0.89[d]	1.48	2.11[d]	4.64	3.2[e]	6.0	1.7[b]	2.5
Po	0.70[bc]	1.27	1.27[bc]	2.58	2.2[abcd]	4.0	1.5[a]	2.7
Ru	0.64[ab]	1.30	1.16[ab]	3.25	2.1[abc]	4.0	1.4[a]	2.5
Wa	0.66[ab]	1.43	1.22[bc]	2.72	2.4[cd]	6.0	1.5[a]	2.8
We	0.69[bc]	1.34	1.13[ab]	3.47	2.4[bcd]	5.0	1.5[a]	2.4
Wr	0.68[bc]	1.24	1.03[ab]	2.16	1.8a	4.0	1.5[ab]	2.6
Mean	0.70	–	1.29	–	2.3	–	1.5	–

$\bar{x}$ – average for strain; max – maximum value for specimens; different letters indicate significant differences among means at $p = 0.05$

According to López et al. [2012] and Zuazo et al. [2013], the paulownia plants have high biomass production. However, the information on paulownia biomass yield in regions with moderate and cold climate zones is limited. The poor soil site allowed the paulownia yield potential to be evaluated in areas of little use for food production. In our study, after the first year of vegetation, the average fresh stem mass was almost 0.1 kg, and the dry mass was approximately 0.03 kg. A density of 10.000 plants ha^{-1} could give an estimated 1.0 t ha^{-1} of fresh and 0.3 t ha^{-1} dry stem mass. However, some strains were more productive (tab. 6). The higher shoot yield might be obtained in cultivating the ‘LuP’ and ‘We’ strains of paulownia. The fast-growing selected paulownia strains could give an estimated 1.4 t ha^{-1} of fresh and 0.4 t ha^{-1} of dry shoot biomass after the first year of vegetation. It should be emphasised that the experiment aimed to select the strongest paulownia strains under extensive cultivation conditions, not to optimise plant yields. A similar biomass production was obtained in the following year (tab. 6). A significant effect of weather conditions was observed. In 2015, limited water availability had a direct impact on biomass production. The vegetation period was significantly dry. The ‘LuP’ strain produced the highest shoot yield among the studied strains. The predicted yield was approximately 1.8 t ha^{-1} fresh and 0.4 t ha^{-1} of dry shoot biomass after the second year of vegetation.

Table 6. The stem mass of the studied paulownia strains in the first two year of vegetation

Year	Strain													Mean
	Bd	Bg	Bl	Cr	Kr	LuB	LuD	LuP	Po	Ru	Wa	We	Wr	
Fresh mass of stem per plant (kg)														
2014	0.06	0.09	0.09	0.10	0.10	0.09	0.11	0.14	0.10	0.09	0.11	0.14	0.08	0.10
2015	0.08	0.09	0.10	0.11	0.11	0.12	0.14	0.18	0.09	0.09	0.10	0.15	0.09	0.11
Dry mass of stem per plant (kg)														
2014	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.04	0.02	0.03
2015	0.02	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.02	0.03
Dry mass content in the stem (%)														
2014	30.5	29.7	29.3	29.8	29.4	27.6	29.8	28.5	29.9	30.2	28.3	29.9	29.8	29.4
2015	27.8	34.5	32.0	32.7	27.4	28.0	20.5	23.9	36.4	31.1	30.0	26.9	22.5	28.7

In the literature, there is limited information about the winterhardiness of paulownia in Polish climatic conditions. In the *Paulownia* genus, the royal paulownia (*P. tomentosa*) is considered the most frost-resistant. It can withstand temperatures as low as below –20°C [Woods 2008]. However, according to Zhu et al. [1986], young trees are susceptible to frost damage. In our experiment, after the first winter period, the average number of dead plants was 19%. In the 2014/15 season, the lowest minimum air temperature was –20.6°C at the ground. Thus, the temperature falls outside this range for paulownia plants. However, significant differences were found among the studied strains (tab. 7). The two fast-growing strains (‘LuP’ and ‘We’) were more winter-hardy. The number of dead plants did not exceed 5%. The third fast-growing strain (‘LuD’) was characterised by slightly lower winterhardiness. The number of dead plants did not exceed 8%. Moderate winter survival was observed in the ‘Ru’, ‘LuB’, ‘Wr’ and ‘Bg’ strains. However, the ‘Po’, ‘Bd’ and ‘Bl’ strains were the least winter-hardy. The number of dead plants was almost 40%. The problem with the winter hardiness of paulownia plants in the Czech Republic was also highlighted by Kadlec et al. [2023].

Table 7. Winter survival of studied paulownia strains after 2014/15 season

Strain	Number of dead plants (%)
Bd	35.0
Bg	17.5
Bl	37.5
Cr	20.0
Kr	27.5
LuB	15.0
LuD	7.5
LuP	2.5
Po	35.0
Ru	10.0
Wa	22.5
We	5.0
Wr	15.0
Mean	19.2

The juvenile paulownia plants have large leaves (fig. 2). They can reach up to 80 cm in width [El-Showk and El-Showk 2003]. In the first year of vegetation, the average leaf blade length reached 25 cm, whereas the leaf blade width was 30 cm. The smaller leaves are likely a result of high plant density and inadequate irrigation. Generally, the 'LuP' and 'We' strains had significantly larger leaves than others (tab. 8). Moreover, the maximal leaf blade length and width of the strongest specimens were almost 45 cm and surpassed 53 cm, respectively. The leaves had relatively long petioles, with a length close to 20 cm and a diameter of 1 cm. However, the petiole size of the strongest specimens was significantly larger. The leaf petioles were almost 40 cm in length and 2 cm in diameter. For all strains, the average fresh and dry leaf mass was 18 g and 5 g, respectively. The leaves of the 'We' strain were heavier than the others (tab. 9). The leaves of paulownia plants are also a valuable source of biomass. The mass of all leaves per plant is slightly heavier than the mass of stems [Liszewski and Bąbelewski 2018b]. Therefore, the aboveground biomass yield can be doubled compared to the previously estimated value.

Fig. 2. Royal paulownia in the second year of vegetation (Grochowe in June and July 2015)

In the second year of vegetation, the paulownia plant had slightly smaller leaves than the previous year (tab. 8). This was probably due to low precipitation during the vegetation period. The average leaf blade reached 15 cm in length and 20 cm in width. Among the studied strains, 'LuP' had significantly larger leaves (tab. 8). Moreover, the leaves of 'LuD' and 'LuP' strains were heavier than the others (tab. 9).

The basic physiological measurements of paulownia leaves were made. Significant differences among strains in the case of relative chlorophyll content were found (tab. 10). Generally, the 'LuP' and 'LuD' strains have the highest SPAD values. However, the third

Table 8. Biometric properties of leaves of studied paulownia strains after the first two year of vegetation

Strain	Length of leaf blade (cm)		Width of leaf blade (cm)		Length of the leaf petiole (cm)		Diameter of the leaf petiole (cm)	
	2014	2015	2014	2015	2014	2015	2014	2015
Bd	22.1^{a}	13.3^{a}	26.4^{a}	16.0^{a}	15.6^{a}	9.0^{a}	0.9^{a}	6.6^{a}
Bg	23.6^{ab}	14.8^{ab}	28.0^{ab}	19.2^{bc}	19.2^{bcd}	12.3^{b}	1.0^{bc}	8.0^{bcd}
Bl	24.5^{bc}	13.7^{a}	30.3^{bcd}	18.1^{ab}	19.6^{bcde}	11.0^{ab}	1.1^{bcde}	7.2^{ab}
Cr	25.0^{bcd}	14.5^{ab}	31.0^{de}	18.9^{abc}	20.9^{def}	12.0^{b}	1.1^{bcde}	7.4^{abc}
Kr	24.6^{bc}	14.2^{ab}	30.2^{bcd}	18.2^{ab}	19.8^{cde}	10.9^{ab}	1.1^{bcde}	7.6^{abc}
LuB	24.7^{bc}	14.5^{ab}	29.5^{bcd}	19.0^{bc}	21.3^{ef}	12.5^{b}	1.1^{cde}	7.9^{bcd}
LuD	23.7^{ab}	15.9^{b}	30.2^{bcd}	21.3^{c}	22.4^{fg}	15.2^{c}	1.2^{de}	8.7^{d}
LuP	26.6^{de}	19.2^{c}	33.3^{ef}	24.4^{d}	24.4^{gh}	16.1^{c}	1.1^{bcd}	8.3^{cd}
Po	23.4^{ab}	14.8^{ab}	29.3^{bcd}	18.9^{abc}	18.2^{bc}	11.2^{ab}	1.0^{b}	7.3^{ab}
Ru	24.4^{bc}	14.8^{ab}	30.6^{cd}	19.4^{bc}	18.6^{bc}	12.2^{b}	1.1^{bc}	7.8^{bcd}
Wa	25.6^{cd}	13.7^{a}	31.4^{def}	18.1^{ab}	19.4^{bcde}	10.6^{ab}	1.1^{bcde}	7.1^{ab}
We	27.4^{e}	14.7^{ab}	33.5^{f}	18.5^{ab}	24.8^{h}	12.4^{b}	1.2^{e}	7.3^{ab}
Wr	23.3^{ab}	14.5^{ab}	28.4^{abc}	18.9^{abc}	17.7^{b}	11.7^{b}	1.0^{b}	7.8^{bcd}
Mean	24.5	15.0	30.1	19.3	20.1	12.3	1.1	7.7

Different letters indicate significant differences among means at $p = 0.05$

Table 9. The leaf mass of the studied paulownia strains in the first two years of vegetation

Year	Strain													Mean
	Bd	Bg	Bl	Cr	Kr	LuB	LuD	LuP	Po	Ru	Wa	We	Wr	
Fresh mass of leaves (g)														
2014	15.2	15.9	19.4	18.6	20.0	17.2	18.0	18.2	17.8	18.3	19.1	21.8	16.9	18.2
2015	5.3	7.7	7.5	8.0	7.3	7.8	10.6	10.6	7.1	7.8	6.9	8.3	8.2	7.9
Dry mass of leaves (g)														
2014	4.2	4.2	5.5	5.1	5.4	5.5	5.4	5.3	5.1	4.8	4.9	6.3	4.6	5.1
2015	1.2	1.7	1.7	1.4	1.2	1.8	2.4	2.4	1.6	1.8	1.5	1.9	1.6	1.7
Dry mass content in the leaves (%)														
2014	28.7	27.3	28.0	27.3	26.0	30.7	30.7	28.7	28.0	27.7	26.3	28.7	28.0	28.2
2015	26.7	22.6	23.0	18.3	19.7	22.9	23.2	22.8	26.8	23.2	22.0	23.3	19.7	22.6

Table 10. Relative chlorophyll content of studied paulownia strains in the first two years of vegetation

Strain	2014	2015
Bd	42.2[ab]	34.4[ab]
Bg	41.4[ab]	32.8[a]
Bl	40.3[ab]	35.7[ab]
Cr	44.2[b]	35.5[ab]
Kr	39.0[a]	34.3[ab]
LuB	43.5[b]	33.4[a]
LuD	44.2[b]	36.5[b]
LuP	44.2[b]	36.3[b]
Po	42.7[ab]	34.6[ab]
Ru	42.5[ab]	34.9[ab]
Wa	40.6[ab]	34.6[ab]
We	39.3[a]	34.5[ab]
Wr	42.3[ab]	34.0[ab]
Mean	42.0	34.7

Table 11. Evaluation of paulownia strains using the quotient method after the first year of vegetation

Strain	Strain index								
	length of the strongest shoot	total length of shoots	number of shoots	diameter of shoot base	fresh mass of stem	dry mass of stem	SPAD index	winter plant survival	sum
Bd	0.85	0.86	1.03	0.88	0.64	0.66	1.00	0.80	6.72
Bg	1.00	1.08	1.09	0.93	0.88	0.90	0.99	1.02	7.90
Bl	0.97	0.94	0.95	0.95	0.86	0.85	0.96	0.77	7.25
Cr	1.02	0.93	0.88	1.03	1.04	1.05	1.05	0.99	7.99
Kr	0.98	0.91	0.90	1.01	0.98	0.97	0.93	0.90	7.57
LuB	0.87	1.08	1.29	0.98	0.87	0.82	1.03	1.05	7.99
LuD	1.01	1.01	1.01	1.06	1.06	1.07	1.05	1.15	8.42
LuP	1.13	1.36	1.30	1.05	1.36	1.32	1.05	1.21	9.79
Po	1.02	0.93	0.88	0.98	1.04	1.06	1.02	0.80	7.74
Ru	0.98	0.93	0.97	0.98	0.92	0.94	1.01	1.11	7.84
Wa	1.09	0.98	0.86	1.06	1.13	1.09	0.97	0.96	8.13
We	1.21	1.13	0.90	1.12	1.44	1.46	0.93	1.18	9.37
Wr	0.90	0.85	0.93	0.96	0.79	0.80	1.01	1.05	7.29
Mean	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8.00

strongest strain (‘We’) was characterised by a slightly lower value for this parameter. In the second year, lower SPAD values were observed, probably due to unfavourable weather conditions during the growing season.

The most productive and winter-hardy paulownia strains were selected using the quotient method. In the two-year study, the highest total index was determined for the ‘LuP’ strain (tab. 11, 12). The plants of this strain were characterised by the most intensive growth, high yield and high winter hardiness. A relatively high index was also determined for the ‘We’ and ‘LuD’ strains.

Table 12. Evaluation of paulownia strains using the quotient method after the second year of vegetation

Strain	Strain index								
	length of the strongest shoot	total length of shoots	number of hoots	diameter of shoot base	fresh mass of stem	dry mass of stem	SPAD index	winter plant survival	sum
Bd	0.85	0.86	1.03	0.88	0.73	0.67	0.99	0.80	6.80
Bg	1.00	1.08	1.09	0.93	0.82	1.00	0.94	1.02	7.89
Bl	0.97	0.94	0.95	0.95	0.91	1.00	1.03	0.77	7.51
Cr	1.02	0.93	0.88	1.03	1.00	1.33	1.02	0.99	8.20
Kr	0.98	0.91	0.90	1.01	1.00	1.00	0.99	0.90	7.68
LuB	0.87	1.08	1.29	0.98	1.09	1.00	0.96	1.05	8.32
LuD	1.01	1.01	1.01	1.06	1.27	1.00	1.05	1.15	8.56
LuP	1.13	1.36	1.30	1.05	1.64	1.33	1.04	1.21	10.06
Po	1.02	0.93	0.88	0.98	0.82	1.00	1.00	0.80	7.43
Ru	0.98	0.93	0.97	0.98	0.82	1.00	1.00	1.11	7.80
Wa	1.09	0.98	0.86	1.06	0.91	1.00	1.00	0.96	7.85
We	1.21	1.13	0.90	1.12	1.36	1.33	0.99	1.18	9.23
Wr	0.90	0.85	0.93	0.96	0.82	0.67	0.98	1.05	7.16
Mean	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8.00

Based on the cluster analysis, paulownia strains were divided into several groups. In 2014, the ‘LuP’ and ‘We’ strains were separated from the others (fig. 3). Generally, these strains were fast-growing, high biomass-yielding and better winter-hardy with higher values of physiological parameters. Thus, selecting valuable paulownia genotypes that are well-adapted to Polish climatic conditions should be possible. The other groups were more complex and consisted of weaker strains (fig. 3). In 2015, the ‘LuP’, ‘LuD’, ‘LuB’ and ‘Cr’ strains stood out.

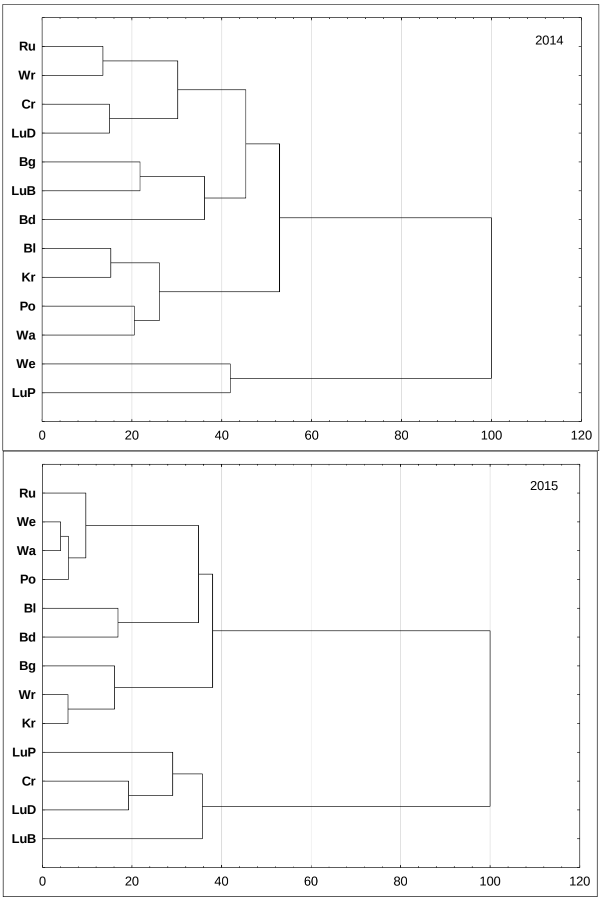

Fig. 3. Similarity of the studied paulownia strains in first two years of vegetation (the following traits were used for agglomeration length and diameter of the strongest shoot, total length and number of shoots, the fresh and dry mass of shoots, SPAD index and winter plant survival)

CONCLUSIONS

Intensive growth and relatively high biomass yield of paulownia plants were confirmed. It is worth emphasising that these plants were grown on poor soil, in high density, with no mineral fertilisation or irrigation. Significant differences were found among studied paulownia strains in growth strength, biomass yield, winter hardiness and the physiological condition. Thus, the 'LuP' strain is most promising for cultivation on poor soil. The fast-growing paulownia 'LuP' strain could give an estimated 1.8 t ha^{-1} of fresh stem biomass after the second year of vegetation. However, in optimal growing conditions, a higher yield can be expected. The leaves of paulownia plants are also a valuable source of biomass. Therefore, the aboveground biomass yield can even be doubled than previously estimated. It may be concluded that the 'LuD' and 'We' strains should also be recommended for cultivation in moderate climate zones. The fast-growing strains were more winter-hardy than others. They were also characterised by a significantly higher SPAD index. It could therefore be argued that the selected strains were more tolerant to abiotic stress.

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Wood waste compost as growing media components for cultivation of *Chrysanthemum morifolium* (Ramat.) Hemsl.

Kompost z odpadów drzewnych jako składnik podłoża do uprawy chryzantemy wielkokwiatowej *Chrysanthemum morifolium* (Ramat.) Hemsl.

Abstract. The chrysanthemum is a significant species grown in Europe in pots and as a cut flower. In the cultivation of this species, peat substrate is used as a medium. The aim of the research was to assess the possibility of using composts from post-consumer wood used for in controlled cultivation of chrysanthemum *Chrysanthemum morifolium* (Ramat.) Hemsl. Mount Listou cultivar. Compost obtained from post-consumer wood waste, were used as the medium, and marked as: PCW I and PCW II. These were old furniture. The third compost marked with the symbol FB was obtained from fiber boards. The substrates used with the addition of compost made on wood waste had an impact on the quality of chrysanthemum. As studies have shown, composts from post-consumer wood they can be a valuable component of horticultural substrates when used appropriately.

Keywords: post-consumer wood, compost, chrysanthemum

INTRODUCTION

The topic of using peat in horticulture raises a lot of concerns and controversy, especially in Europe. The exploitation and degradation of peatlands contributes to global greenhouse gas emissions. Its exploitation degrades the environment and increases CO_2 emissions into the atmosphere (1 billion tons CO_2 per year) [Bonn et al. 2014, Tubiello et al. 2016]. In various countries, there are regulations forcing the reduction of its consumption. In the many European country such as: Germany, Ireland, United Kingdom, Norway,

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the government has set specific goals to eliminate horticultural peat use by amateur (2025–2026) and by professionals (2030) [Hirschler et al. 2022, Hirschler and Thran 2023].

The introduced restrictions on the use of peat require the search for alternative substrates that will allow its elimination in horticultural production [Gioia et al. 2017]. Giving up peat substrates in favor of other substitutes is not easy because peat is characterized by, among other things, very good chemical, biological and physical properties [Gruda 2012, Diaspenza et al. 2016, Savvas and Gruda 2018, Gruda 2019, Zulfiqar et al. 2021].

Due to envirnomental concerns and political decision regarding the use of peat, substrates that can replace peat in production are being sought.

Wood is one of the most commonly used natural materials. Wood waste is an inherent result of the wood harvesting and processing process, as well as human activities. According to Kurowska [2016], there are three groups of wood waste: forest, industrial, and post-consumer waste. Post-consumer wood waste is the most diverse group among those mentioned. The elements of waste wood are most often old furniture, doors, windows, floors, construction materials, packaging, and other wooden products that have completed their life cycle [Komorowicz et al. 2021].

One of the oldest industrial activities in the world is furniture production, which is an inseparable part of everyday life. As much as 77% of furniture production takes place in 10 countries, with Poland being one of the most important producers. The assumptions of the European Green Deal stipulate that the products being introduced must be designed in such a way as to align with the concept of a circular economy and sustainable development through the rational management of products that have waste status [Nguyen et al. 2023]. Organic recycling of wood waste can be composting, that is, the transfer of biodegradable waste under controlled conditions using microorganisms (actinomycetes, bacteria and fungi) to produce organic matter. For example, *Lactobacillus plantarum* may accelerate the decomposition and fermentation in composting process. *Streptomyces albus* produce antibacterial matter for pathogenic bacteria and *Rhodobacter sphaeroides* involve in production of amino acids and amino nucleic. *Saccharomyces cerevisiae* and *Candida utilis* promote fermentation and produces bioactive substances. Likewise, fungal species *Aspergillus*, *Trichoderma*, *Sclerotinum* and white rot fungi, produce extracellular enzymes accountable for cellulose and lignin degradation during composting [Muttalib et al. 2016, Rastogi et al. 2020].

In recent years, composted organic waste has been increasingly used as growing media due to its high content of organic matter and nutrients, and because it enables the reuse of waste materials [Atzori et al. 2021].

One possibility of using wood waste for the disposal of materials of wood origin may be composting this waste. Disposal of post-consumer wood waste has recently become increasingly popular in the European Union. Composted materials obtained from wood waste after consumption can be used as a source of humus and organic substances [Komorowicz et al. 2021]. Wood waste comprises almost 90% of the organic matter including carbohydrates (65–75%) and lignin (18–35%) [Rowell et al. 2012].

The potted chrysanthemum is a very popular because it has many varieties of different colors, size and type of flowers [Singh et al. 2023, Lu et al. 2024]. Thanks to controlled cultivation, flowering plants are available all year round.

The aim of the research was to assess the possibility of using composts from post-consumer wood as a component of the substrate for growing chrysanthemums and to obtain good quality plants.

MATERIAL AND METHODS

The research was carried out in controlled cultivation on chrysanthemum (*Chrysanthemum morifolium*) Mount Listou as a model plant from horticultural farm A.A. Kłak (Szczepankowo, Poland). Rooted cuttings were pinched off above the fifth leaf and planted five pieces each into pots of 14 cm diameter and a volume of 1 dm^3. In order to obtain a compact habit, the growth retardant – daminozide (2550 mg dm^{-3}), contained in the Dazide Enchance 85 SG preparation was used twice.

Beginning from the second week of cultivation, fertigation was applied using Superba Brown (10% $N\text{-}NO_3$ and 4.1% $N\text{-}NH_4$, 9.2% P_2O_5, 25.4% K_2O, 2.8% MgO, 6% SO_3, 0.16% Fe, 0.1% Mn, 0.02% Zn, 0.007% Cu, 0.03% B, 0.002% Mo) in the concentration of 0.1%.

From the moment the plant was planted, it was grown under short day conditions, shortening the day with the help of shading curtains (figure 1).

Fig. 1. Controlled chrysanthemum cultivation in plastic tunnel

Compost obtained from post-consumer wood waste were used as the medium, and marked as: PCW I and PCW II. These compost consisted of old kitchen furniture. The third compost marked with the symbol FB was obtained from fiber boards. Selected waste was preliminarily crushed.

The composting process was conducted in three 160 dm^3 volume chambers of the bioreactor of each for a period of three months.

The chambers of the bioreactor contained:

I. PCW I – post-consumer wood (70%), powdery waste from processing MDF boards (6%), mature compost made from fiber board waste (19%), high peat (4%), $CO(NH_2)_2$ (20 kg), Activit Las,

II. PCW II – post-consumer wood (70%), powdery waste from processing MDF boards (6%), mature compost made from fiber board waste (19%), high peat (4%), NH_4NO_3 (1.5 kg), $MgSO_4$ (0.4 kg), K_3PO_4 (0.8 kg), $Ca_3(PO_4)_2$ (0.9 kg), Activit Las,

III. FB – fiber boards waste (65%), pine shavings (28%), high peat (7%), $CO(NH_2)_2$ (20 kg), Activit Las.

A biological inoculum Activit Las containing bacteria, actinomycetes, and fungi *Trichoderma* sp., *Penicillium* sp. The composted wood waste is shown in figure 2.

Fig. 2. The composted wood waste

The plants were cultivated in mediums consisting of peat substrate with addition PCW I, PCW II or FB composts in different proportions (25%, 50%, 75%). The control plants were grown in peat substrate TS1 Klasmann-Deilmann (GmbH Geeste, Germany). The parameters of composts before mixing with peat and the chemical composition of the medium before and after cultivation are presented in tables 1–3.

Table 1. The content of dry mass, ash, density in the peat substrate and composts before mixed

Medium	Dry mass	Ash	Density	Organic carbon	Total nitrogen	C : N ratio
	%		$g\ dm^{-3}$	$g\ kg^{-1}$		
Peat substrate	31.9	15.8	330	52.9	0.9	56.2 : 1
PCW I	32.3	11.6	324	403.6	36.1	11.2 : 1
PCW II	32.6	12.1	319	401.0	25.1	16.0 : 1
FB	31.7	11.2	322	417.3	15.1	28.0 : 1

Table 2. The chemical composition before plant cultivation (C – compost, PS – peat substrate)

Medium		$N\text{-}NO_3$	P	K	Ca	Mg	Fe	Mn	Zn	Cu	Cl	Salnity g NaCl dm^{-3}	pH
		mg $\cdot dm^{-3}$											
Control – peat substrate		91	64	39	2491	127	47.4	4.2	5.6	1.12	39	1.23	6.0
PCW I	75% C + 25% PS	321	27	51	894	56	51.4	13.2	694	0.96	53	1.98	5.1
	50% C + 50% PS	276	29	45	987	61	49.1	11.3	327	0.75	42	1.85	5.5
	25% C + 75% PS	210	25	40	1250	60	37.2	9.8	205	0.47	49	1.72	6.0
PCW II	75% C + 25% PS	430	35	55	872	67	54.2	14.7	591	0.48	47	2.31	5.2
	50% C + 50% PS	378	34	51	1124	70	47.6	12.5	324	0.42	56	1.46	5.8
	25% C + 75% PS	223	34	47	1435	72	41.5	10.8	217	0.39	61	1.18	6.2
FB	75% C + 25% PS	147	42	38	483	20	79.0	53.1	12.3	2.7	27	2.04	5.5
	50% C + 50% PS	142	51	76	536	31	64.0	47.2	10.7	3.4	37	2.01	5.8
	25% C + 75% PS	117	50	70	587	28	69.0	45.1	9.8	4.2	40	1.96	5.4

Table 3. The chemical composition of the medium after plant cultivation (C – compost, PS – peat substrate)

Medium		$N\text{-}NO_3$	P	K	Ca	Mg	Fe	Mn	Zn	Cu	Cl	Salnity g NaCl dm^{-3}	pH
		mg dm^{-3}											
Control – peat substrate		391	112	110	2628	210	21.9	2.54	6.2	1.37	81	1.9	5.6
PCW I	75% C + 25% PS	246	37	62	1108	102	37.9	12.7	602	2.78	224	2.25	5.0
	50% C + 50% PS	321	26	49	1456	141	32.7	10.2	357	1.84	356	2.02	5.8
	25% C + 75% PS	237	32	38	1827	162	26.2	8.7	196	1.56	407	2.71	6.0
PCW II	75% C + 25% PS	296	26	50	927	98	46.3	9.1	478	1.12	169	1.8	5.5
	50% C + 50% PS	312	31	48	1532	106	32.9	5.2	322	1.41	174	2.4	5.6
	25% C + 75% PS	152	30	21	1967	124	34.1	2.1	207	1.03	182	2.3	6.1
FB	75% C + 25% PS	129	39	37	826	27	76.0	42.7	11.9	2.81	51.2	2.1	5.4
	50% C + 50% PS	120	40	56	921	33	61.0	45.1	10.2	3.62	60.7	1.96	5.7
	25% C + 75% PS	112	42	50	992	31	60.0	39.8	8.7	3.91	69.8	1.92	5.5

The collected substrate samples were subjected to chemical analysis using universal methods described in the methodology published by Schroeter-Zakrzewska et al. [2021].

When the one half off flowers was developed biometric measurements were taken such as the: height and diameter of plants, the number of leaves, flowers, flower buds and the diameter of flowers. The diameter of flowers was measured using electronic calliper. The height and diameter of the plants were measured using a ruler. On the last day of the experiment the chrysanthemum were cut and the aboveground parts was weighed. Then the fresh mass was marked using an electronic balance. Then, they were dried in a drier for 48 h at 60°C and weighed to mark the dry weight.

The green leaf index SPAD (Soil Plant Analysis Development) was measured using of Yara N-Tester apparatus. The mean sample consisted of 36 leaves per one combination (3 leaves for each pot). The size of leaf area was measured using of WinDIAS 3.2 (Delta-T Devices).

The experiment consisted of 10 combinations and 12 replications, were 1 replication was 1 pot. The experiment was established in 2 culture cycles. The results of measurement given as mean from 2 cycles.

The results were statistically analyzed using Statistica 13.0 software. The averages were grouped using Duncan's test at a significance level of $p = 0.05$.

RESULTS AND DISCUSSION

The results of chemical analysis of medium before cultivation indicate differences in the content of nutrients, pH and salinity (table 2). The high Zn content was determined in medium containing PCW I and PCW II compost, both at the beginning and after the end of cultivation. This is probably due to the presence of zinc white used in the production of paints used to cover post-consumer wood. FB compost had a low content of this element (tables 2–3).

The quality of chrysanthemum depended on the type of medium (tables 4–5, figure 1). The plants cultivation in medium with 50% PCW I compost and 25% PCW II compost were slightly taller and wider than the other plants. The taller plants of *Leucanthemum maximum* but with smaller diameter were obtained by Kozik et al. [2010] growing the plants in media with fiber board compost and mineral soil.

The compost containing medium used, with the exception of the 25% PCW I and PCW II compost, significantly stimulated leaf formation. The plants cultivation in medium with 75% FB compost were characterized by the highest number (27 more compared to control plants).

Schroeter-Zakrzewska et al. [2021] also observed the stimulating effect of compost on leaf formation in the cultivation of zonal geraniums with the exception of plants grown in compost alone.

The leaf greenness index was significantly dependent on the medium used. The lower SPAD values were recorded in plants growing in media containing PCW I and PCW II compost. The reason could be the high Zn content, which can block the uptake of other microelements. According to Zawadzińska et al. [2021], geraniums grown in a medium containing 40% wood fibers formed brighter leaves, which was associated with lower leaf greenness index, compared to control plants. The low SPAD values under the influence of wood waste composts were observed by Wróblewska et al. [2013, 2014] and by Adamczewska-Sowińska et al. [2021].

The leaf area, as well as weight of the chrysanthemum grown in the compost supplemented medium was greater compared to the plants growth in the peat substrate. A positive effect of using compost that included wood fibers, pecan wood, willow wood and post-consumer wood was obtained by Brito et al. [2015], Picchioni et al. [2016], Schroeter-Zakrzewska et al. [2021], Bekier et al. [2022]. Also research by Kozik et al. [2010] show an increase in the fresh weight of *Leucanthemum maximum* after the application of compost obtained from waterproof plywood waste. In the case of *Geranium sanquineum,* the above mentioned authors showed no differences in plant weight after the application of compost. The study by Adamczewska-Sowińska et al. [2021] showed that cucumber grown on substrates with the addition of willow compost (75% or 50%) had a similar weight as cucumber grown on peat substrate. On the other hand, the negative effect of application of post-consumer wood compost at 100%, 75%, 50% on the fresh weight and leaf area of canna lily is reported by Wróblewska et al. [2014].

Table 4. Vegetative characteristics of the chrysanthemum depending on the medium (C – compost, PS – peat substrate)

Medium		Height of plants (cm)	Plant diameter (cm)	Number of leaves	Green leaves index (SPAD)	Leaf area (cm^2)	Fresh weight (g) per pot	Dry weight (g) per pot
Control – peat substrate		15.8 a*	18.6 b	132.6 a	56.9 bcd	12.2 a	68.5 a	5.8 a
PCW I	75% C + 25% PS	14.9 a	17.0 a	152.1 b	49.8 a	15.4 c	105.9 c	9.8 bc
	50% C + 50% PS	17.1 b	19.9 c	146.2 b	54.8 bc	15.7 c	100.0 c	9.4 bc
	25% C + 75% PS	14.8 a	19.3 bc	131.4 a	54.9 bc	14.1 b	102.8 c	10.1 c
PCW II	75% C + 25% PS	14.6 a	16.8 a	145.9 b	53.5 ab	15.1 c	94.7 b	7.8 b
	50% C + 50% PS	15.1 a	18.6 b	159.5 b	55.0 bc	15.6 c	91.3 b	8.3 b
	25% C + 75% PS	16.9 b	20.1 c	138.2 a	55.2 bc	14.5 b	123.2 d	12.4 d
FB	75% C + 25% PS	14.9 a	18.3 b	160.1 c	57.5 bcd	14.9 b	94.7 b	8.9 b
	50% C + 50% PS	15.6 a	18.5 b	153.8 b	58.1 cd	15.2 c	104.0 c	10.2 c
	25% C + 75% PS	15.8 a	19.1 b	147.6 b	60.2 d	14.7 b	112.0 cd	11.1 c

*means followed by different letters are significantly differ $p = 0.05$

The quality of chrysanthemums is primarily determined by the number of flowers. Only plants that flower abundantly attract buyers.

The present research showed that the composts used in the study had a significant effect of plant flowering (table 5). The highest number of flowers was observed in plants grown in media with 50%, 25% PCW I compost and 25% PCW II compost addition. Lu et al. [2024] observed significant differences in the growth of chrysanthemum Hanluqiushi cv. depending on the cultivation substrate. The plants grown in a substrate composed of coir, moss peat, perlite, and pine needle soil in a 2:4:2:2 ratio developed flowers with a larger diameter compared to the control group.

The lower number of flower head was characteristic for plants grown in a media with FB composts. A similar trend obtained by Kozik et al. [2010] in *Leucanthemum maximum* cultivation in fiber boards composts. Wróblewska et al. [2014] observed that use of wood waste composts at 25% and 50% has no effect on the flowering of petunia. According to the literature, plant flowering will be influenced by species, compost composition and percentage of compost in the medium [Wróblewska et al. 2014, Zawadzińska et al. 2021].

A higher proportion of compost (75%) in the substrate influenced a decrease in the number of inflorescence buds. Cultivation of plants in substrates with the addition of compost resulted in the formation of flowers with a larger diameter of flower heads, except for the use of substrates with a 25% share of compost. Smaller flowers of marigold and French marigold were obtained by Gariglio et al. [2004] after using a substrate with 75% willow sawdust.

Table 5. Generative characteristics of the chrysanthemum depending on the medium (C – compost, PS – peat substrate)

Medium		Number of flower head	Number of flower buds	Diameter of flower head (cm)
Control – peat substrate		37.5 b*	74.6 c	8.0 a
PCW I	75% C + 25% PS	36.8 b	43.5 a	8.3 b
	50% C + 50% PS	41.5 c	76.6 c	8.3 b
	25% C + 75% PS	43.6 c	80.5 d	8.0 a
PCW II	75% C + 25% PS	36.1 b	56.0 b	8.5 c
	50% C + 50% PS	35.3 b	60.5 b	8.5 c
	25% C + 75% PS	45.1 d	73.9 c	8.0 a
FB	75% C + 25% PS	33.1 a	58.6 b	8.3 b
	50% C + 50% PS	32.6 a	72.4 c	8.3 b
	25% C + 75% PS	31.6 a	76.6 c	8.0 a

* means followed by different letters are significantly differ $p = 0.05$

Fig. 3. The chrysanthemum cultivated in the substrates with 50% share of composts and in control (1 – PCW I, 2 – PCW II, 3 – FB, 4 – control-peat substrate)

CONCLUSIONS

The applied substrates with the addition of composts made from post-consumer wood had an effect on the quality of chrysanthemum. Taller and wider plants were formed after applying a medium with 50% addition of PCW I and PCW II compost. Adding compost to the substrate stimulated the formation of leaves, which were characterized by a larger leaf blade area. The fresh and dry plant matter was also higher compared to plants grown in peat substrate. The composts used (with the exception of FB compost) adversely affected the leaf greenness index, whose values were lower in relation to plants grown in peat substrate. The greatest number of flower heads was observed in plants cultivated in substrates containing 50% and 25% of PCW I compost as well as those with 25% addition of PCW II compost. A higher proportion of compost (75%) in the substrate influenced a decrease in the number of inflorescence buds.

Since ornamental plants are valued for their appearance, it is recommended to grow chrysanthemums in a substrate consisting of peat and compost in rations of 75:25% or 50:50% by volume. Better plant quality with a higher proportion of peat in the substrates is likely due to the improvement of air-water relations in the substrate.

This approach not only supports the production of high-quality plants but also significantly reduces peat usage, thereby aiding in the preservation of peatland ecosystems.

As studies have shown, composts from post-consumer wood can be a valuable component of horticultural substrates when used appropriately. The conducted research indicates that composts made from post-consumer wood waste meet the requirements for soil improvers or peat substitutes in horticultural substrates according to Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products.

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The effect of fertilization and irrigation on potato yield in organic production system

Wpływ nawożenia oraz nawadniania na plonowanie ziemniaka w ekologicznym systemie produkcji

Abstract. The study conducted in 2018–2020 aimed to determine the effect of irrigation and varied organic fertilization on potato yield, structure and chemical composition of tubers in an organic production system. Supplemental irrigation was carried out using a drip system. The fertilizer facilities were: Humac Agro; manure; manure + Humac Agro; vermicompost; vermicompost + Humac Agro; Fertil CN; Fertil CN + Humac Agro. Fertil CN applied alone and together with Humac Agro had the highest yield-forming efficiency; the average increase in total tuber yield in these fertilizer variants was 15.0 t ha^{-1} (87.2%), and in marketable yield by 15.8 t ha^{-1} (139.8%). Irrigation had a favorable effect on the accumulation of total and marketable tuber yield, the number of tubers set and their average weight, as well as their protein content. The irrigation water use efficiency (IWUE) index was in a wide range from 24.5 to 123.8 kg mm^{-1} depending on the fertilizer variant and the year of the study.

Key words: *Solanum tuberosum*, tuber yield and its structure, chemical composition of tubers, water-use efficiency

INTRODUCTION

The agriculture of developed countries, which is characterized by a high degree of chemicalization, contributes to the environmental crisis, which has been widely reported for a long time. The intensive type of farming focuses primarily on maximizing production and thus profit, while environmental considerations are often overlooked. International

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organizations such as the United Nations and the European Union, bringing together many countries, are introducing resolutions aimed at reducing the negative impact of agriculture on the environment. One such provision is the introduction of the principles of sustainable agriculture. The model of sustainable agriculture implies the realization of production goals while maintaining the principles of environmental safety. The main provisions of the principles of sustainable development consist in reducing the degree of use of chemical means of production and replacing them with non-chemical solutions. These goals can be achieved in an integrated and, above all, in an organic agricultural production system. While meeting the requirements of integrated agriculture is not overly burdensome, the organic system is much more demanding. Regulations on organic farming, describe in detail the practices that should be followed. One of them is the complete abandonment of synthetic mineral fertilizers and replacing them primarily with organic fertilizers.

Trends in organic potato cultivation vary from region to region around the world. For example, in the USA, organic potato cultivation doubled between 2008 and 2016, while in Poland, organic potato, despite significantly higher market prices, is reluctantly grown [Nowacki 2020, Rana and Jhilta 2021]. Statistical data indicate a reduction in the area under organic potato cultivation resulting from the high threat from weeds, disease perpetrators and pests [Rogacz 2019]. The share of potato in the total area of organic crops in 2022 accounted for only 0.3% in Poland [IJHARS 2023]. In order to facilitate potato production in the organic system organic fertilizers that are more efficient in terms of bioavailability and use as well as more effective methods of controlling disease and pests should be developed [Ezov et al. 2020]. Potato is a crop that responds favorably to organic fertilization [El-Sayed et al. 2007, 2015]. In addition to providing essential macro- and micronutrients, natural and organic fertilizers are also a source of organic matter, which is responsible for the physical, chemical and biological properties of the soil [Alvarez et al. 1988, Kowalska et al. 2017]. Organic farmers are obliged to use fertilizers of natural origin, primarily various types of composts and green manures.

The level of potato yield significantly depends on the amount and distribution of precipitation during the plant's growing season, and water needs are related to cultivar earliness, genetic characteristics and climatic conditions. The minimum water needs of the potato in temperate climates are about 250 mm, but already in sub-equatorial climates they are 750 mm [Gitari et al. 2018]. Deficiencies in precipitation, especially during tuberization and intensive tuber weight gain, result in stunted plant development, reduced yields and deterioration of tuber quality due to the potato's shallow root system [English and Raja 1996, King et al. 2020]. Despite its high water needs and shallow root system, the potato is considered a water-efficient crop [Vreugdenhil et al. 2011].

The aim of the study was to determine the effect of varying organic fertilization, humic acid application and supplemental drip irrigation on yield, its structure and chemical composition of potato tubers in the organic system.

MATERIAL AND METHODS

Experiment localization and scheme

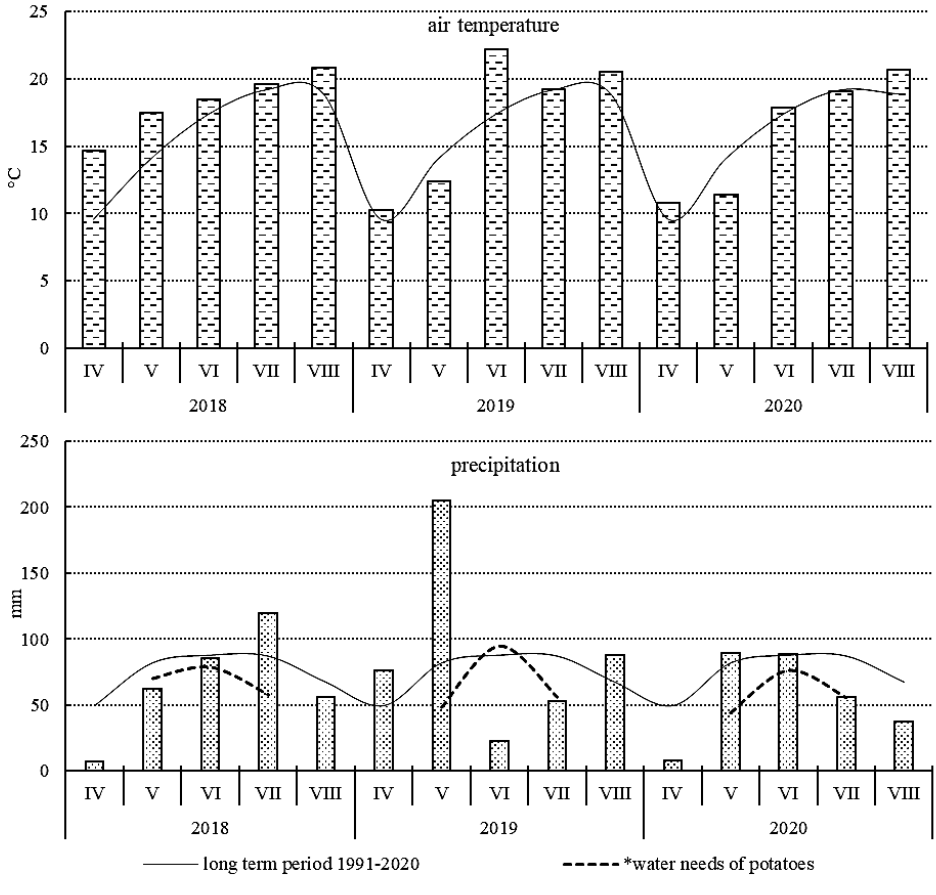
The study was carried out in 2018–2020 at the Experimental Station in Prusy (50°07'N and 20°05'E) belonging to the University of Agriculture in Kraków. The field experiment was established in a randomized sub-block (split-plot) arrangement in 3 repetitions. The plot on which the experiments were conducted had been in the ecological system since 2013. The forecrop for potato in all years of the study was buckwheat. The factors of the experiment were organic fertilization and irrigation. The dose selection followed the manufacturers fertilizer recommendations. Fertilizer variants included: control (no fertilization) – C; Humac Agro (400 kg ha^{-1}) – HA; manure (30 t ha^{-1}) – FYM; manure + Humac Agro (30 t ha^{-1} + 400 kg ha^{-1}) – FYM + HA; vermicompost (10 t ha^{-1}) – VC; vermicompost + Humac Agro (10 t ha^{-1} + 400 kg ha^{-1}) – VC + HA; Fertil CN 40–12.5 (600 kg ha^{-1}) – FCN; Fertil CN 40–12.5 + Humac Agro (600 kg ha^{-1} + 400 kg ha^{-1}) – FCN + HA. The fertilizer rates in the combined treatments matched the full agronomic recommendations for each product. This approach was adopted to evaluate a potential synergistic effect between the organic fertilizer and humic acids. The total nitrogen supplied remained below the statutory limit of 170 kg N ha^{-1} for organic farming, thus complying with Regulation (EU) 2018/848 [Schmidt 2019]. Humac Agro contained 79% organic matter, 62% humic acids, 16.8 g Fe kg^{-1}, 15.7 g Na kg^{-1}, 15.1 g Ca kg^{-1}, 1.2 g K kg^{-1}, 77 mg B kg^{-1}, 64 mg Zn kg^{-1}, 19 mg Cu kg^{-1}. The characteristics of the other fertilizers are shown in table 1. The total nitrogen input for each treatment was as follows: HA – 0 kg N ha^{-1}, FYM – 163 kg N ha^{-1}, FYM + HA – 163 kg N ha^{-1}, VC – 101 kg N ha^{-1}, VC + HA – 101 kg N ha^{-1}, FCN – 66 kg N ha^{-1}, FCN + HA – 66 kg N ha^{-1}. Irrigation was carried out using a subsurface (5 cm) T-Tape drip line system. Drip lines with water emitters spaced every 20 cm were distributed on the top of ridges. Irrigation timing was determined based on soil moisture using tensiometers. Irrigation treatments were started when the soil water potential reached –40 kPa [Bailey 2000]. The total amount of water used for irrigation was 78 mm in 2018, 101 mm in 2019 and 84 mm in 2020. Tubers of the early potato cultivar Vineta were planted at a spacing of 75 × 30 cm in the 2nd decade of April, while harvesting was in the 3rd decade of August. The size of the harvest plot was 24 m^2. During the study, there were no significant differences in potato beetle intensity or weed infestation levels between the analysed sites and study years. Slightly higher plant infestation by the potato blight was recorded in the 2018 season. For potato protection against blight, Copper Max New 50 WP (2 kg ha^{-1}) was applied twice, while SpinTor 240 SC (0.15 dm^3 ha^{-1}) was applied against beetle. Weed control was carried out mechanically by inter-row cultivation combined with earthing-up of ridges-first at crop emergence and again about two weeks later. Weeds growing within the rows were removed manually. No herbicides were used, in accordance with organic-farming standards.

Table 1. Physio-chemical parameters of organic fertilizers

Parameter	Farmyard manure	Vermicompost	Fertil CN 40–12.5
pH	7.1 ±0.5	7.4 ±0.3	4.8
Dry matter (g kg^{-1})	265.1 ±15.6	311.0 ±17.5	954.0
Total N (g kg^{-1})	20.5 ±2.6	32.4 ±1.9	115.2
Total C (g kg^{-1})	394.2 ±13.4	298.1 ±9.7	427.4
C/N	19.5 ±1.8	9.2 ±0.2	3.7
Total P (g kg^{-1})	6.2 ±0.5	12.9 ±0.8	10.5
Total K (g kg^{-1})	23.7 ±1.7	38.4 ±1.9	2.1
Total Mg (g kg^{-1})	3.9 ±0.5	9.9 ±0.8	1.3
Total Ca (g kg^{-1})	10.6 ±0.9	18.3 ±1.3	62.3

Soil and meteorological conditions

The field experiment was located on Haplic Chernozem (*Siltic*), classified as very good wheat complex and soil quality class I. The arable layer of soil (0–30 cm) was characterized by: average abundance of phosphorus (50.0–53.0 mg P kg^{-1}), potassium (162.5–187.5 mg K kg^{-1}) and magnesium (49.2–52.0 mg Mg kg^{-1}), slightly acid reaction (pH$_{KCl}$ 5.7–5.8), content of sand 115–126 g kg^{-1}, dust 531–540 g kg^{-1}, clay 334–345 g kg^{-1}.



* water needs according to Klatt [Nyc 2006]

Fig. 1. Characteristics of weather conditions

The characteristics of precipitation-thermal conditions are shown in Figure 1. In 2018 and 2020, the sum of precipitation from April to August was lower than the multi-year average, by 44 mm (12%) and 95 mm (25%), respectively, while in 2019 it was higher by 70 mm (19%). The distribution of precipitation in all years of the study was uneven. Significant precipitation shortfalls in relation to the needs of early potatoes occurred in April 2018 and 2020 and June 2019, while excessive precipitation was recorded in July 2018 and May 2019 and 2020. Analyzing the course of thermal conditions in each year of the study, the air temperature was found to be significantly higher than in the corresponding multi-year period. The average air temperature in the April–August period in 2018 was higher by 2.4°C, in 2019 by 1.8°C, and in 2020 by 1.3°C.

Evaluation of tuber yield and its structure and irrigation efficiency

Prior to potato harvest, tubers were sampled from 10 plants in each plot to determine the number of tubers per plant and the share of the commercial and large tuber fractions (with transverse diameter > 35 and > 50 mm, respectively) in the yield. At harvest, the total tuber yield was determined, while the marketable yield was estimated on the basis of the share of the marketable fraction by separating greened and deformed tubers. Starch content was determined using a hydrostatic balance, total protein by the Kjeldahl method (N × 6.25), while nitrate (V) by potentiometric method.

Water use efficiency (WUE) for each treatment was calculated as tuber yield divided by seasonal evapotranspiration (ET_a):

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ET_a}}$$

where: Y is the tuber yield (kg ha^{-1}); ET_a is seasonal evapotranspiration (mm)

$$\mathrm{ET_a} = \mathrm{P} + \mathrm{I} - \mathrm{D} \pm \Delta\mathrm{W}$$

where: P is the rainfall (mm); I is the irrigation applied to individual plots (mm); D is the deep percolation; ΔW is the change in the water storage of the soil profile (mm). Because irrigation water was applied only in amounts sufficient to replenish soil-moisture deficits up to field capacity, deep percolation beyond the root zone was considered negligible and therefore omitted from the analysis.

Irrigation water use efficiency (IWUE) was determined as:

$$\mathrm{IWUE} = \frac{(\mathrm{Y_I} - \mathrm{Y_{NI}})}{\mathrm{I}}$$

where: Y_I is the tuber yield of irrigation treatments (kg ha^{-1}); Y_{NI} is the tuber yield of non-irrigation treatment (kg ha^{-1}); I is the amount of irrigation water (mm).

Statistical analysis

The results were subjected to statistical evaluation using an analysis of variance. Highly significant differences (HSD) for the investigated features were verified using Tukey's test at a significance level of $P < 0.05$.

RESULTS AND DISCUSSION

Yield and yield structure of tubers

The potato tuber yield significantly depended on the fertilizer variant, irrigation and weather conditions during the growing season. The total tuber yield ranged from 15.9 to 36.6 t ha^{-1}, while the marketable yield ranged from 9.9 to 31.6 t ha^{-1} (tab. 2). The use of drip irrigation resulted in an increase in total tuber yield in each fertilizer variant ranging from 2.5 t ha^{-1} (16%) to 8.6 t ha^{-1} (31%), and marketable yield from 2.7 t ha^{-1} (27%) to 9.4 t ha^{-1} (44%). The largest yield increase was found after the application of Fertil CN fertilizer, and the smallest on the control object – without fertilizer. In a study by Kolodziejczyk [2021], the largest increase in tuber yield on irrigated objects was obtained after the application of vermicompost. Among the organic fertilizers evaluated, Fertil CN had the highest yield-forming efficiency. Manure and vermicompost, which according to Lazcano and Dominguez [2011] and Lim et al. [2015] is a soil-friendly organic fertilizer had a significantly lower yield-forming efficiency. The superior efficiency of Fertil CN is due to the synchronisation of nutrient availability with the temporal demand of the potato. This fertiliser contains 115 g N kg^{-1} d.m. with a very low C to N ratio, which enables rapid mineralisation and a rapid increase in the content of available nitrogen forms at the critical moment of demand [Selim et al. 2010]. The formulation additionally provides easily soluble calcium and humic acids to increase soil sorption capacity and root system length [Palta 2010]. In all fertilizer variants, the beneficial effect of humic acids on potato yield was found, but their effect on the value of these traits was not statistically confirmed. The combined application of organic fertilizers and humic acids resulted in an increase in total and marketable tuber yield in a small range of 1% to 3%. Similar results were obtained by Selim et al. [2010], who applied humic substances through a drip irrigation system. A significantly higher efficiency of humic acids was demonstrated by Ekin [2019]. The author, applying 400 kg HA ha^{-1}, obtained tuber yields at a level equivalent to mineral fertilization of 100+50+50 kg NPK ha^{-1} and 44% higher than on the control object.

During the three-year study period, the highest tuber yields were obtained in 2018 and 2020. However, the lowest yields were recorded in 2019, mainly due to very little rainfall and high air temperature during the tuberization period. The key limiting factor for potato yields in 2019 was probably a shortage of rainfall and high air temperature in June. A similar relationship for the very early cultivar was also shown by Elzner et al. [2018]. According to Burton [1981], the optimum temperature for photosynthesis in European potato cultivars is about 20°C, and each 5°C increase of leaf temperature reduces the rate of photosynthesis by about 25%. Rykaczewska [2015] showed that heat stress combined with water deficit lasting for two weeks during the potato flowering period could reduce the yield of sensitive cultivars by 50%, and tolerant cultivars by 25%.

According to Ruiz de Galarreta et al. [2006] and Kołodziejczyk [2014], the level of potato yield is determined mainly by the average tuber weight, and to a lesser extent by the number of tubers set. Learning about the relationships occurring between yield components is an important issue of potato cultivation, especially in relation to habitat conditions, crop management and plant cultivar characteristics. In the conducted study, the average tuber weight was in a wide range from 59.9 to 115.8 g, depending on the fertilizer variant, irrigation and the year of research. The highest average tuber weight was found after the application of Fertil CN, significantly lower on objects fertilized with manure and vermicompost, and the lowest on the control object. The combined application of humic acids with organic fertilizers had no effect on the formation of

Table 2. Potato tuber yields (t ha^{-1})

Fertilization	Irrigation		Year			Mean
	I_0	I_1	2018	2019	2020	
total tuber yield						
C*	15.9^{c}	18.4^{c}	16.7^{c}	15.7^{c}	19.1^{d}	17.2^{d}
HA	16.8^{c}	19.5^{c}	17.0^{c}	16.8^{c}	20.8^{d}	18.2^{d}
FYM	23.9^{b}	30.6^{b}	30.2^{b}	22.9^{b}	28.7^{b}	27.3^{bc}
FYM + HA	24.3^{b}	31.3^{b}	31.3^{b}	22.8^{b}	29.5^{bb}	27.8^{b}
VC	23.2^{b}	29.5^{b}	31.5^{b}	21.5^{b}	25.9^{c}	26.3^{c}
VC + HA	23.3^{b}	30.6^{b}	31.5^{b}	22.1^{b}	27.3^{bc}	27.0^{bc}
FCN	27.8^{a}	36.3^{a}	34.6^{a}	26.5^{a}	35.1^{a}	32.1^{a}
FCN + HA	28.0^{a}	36.6^{a}	35.1^{a}	26.3^{a}	35.6^{a}	32.3^{a}
Mean	22.9^{b}	29.1^{a}	28.5^{a}	21.8^{b}	27.7^{a}	–
marketable tuber yield						
C	9.9^{c}	12.6^{c}	11.0^{c}	9.7c	13.1^{d}	11.3^{d}
HA	10.8^{c}	13.8^{c}	11.3^{c}	11.1c	14.6^{d}	12.3^{d}
FYM	18.7^{b}	25.6^{b}	24.7^{b}	16.8b	25.1^{b}	22.2^{bc}
FYM + HA	18.8^{b}	26.0^{b}	25.0^{b}	16.8b	25.3^{b}	22.4^{b}
VC	17.9^{b}	24.3^{b}	25.6^{b}	15.9b	21.8^{c}	21.1^{c}
VC + HA	17.7^{b}	25.5^{b}	25.8^{b}	15.7b	23.2^{bc}	21.6^{bc}
FCN	22.2^{a}	31.6^{a}	28.4^{a}	20.6a	31.8^{a}	26.9^{a}
FCN + HA	22.7^{a}	31.8^{a}	28.9^{a}	20.6a	32.2^{a}	27.3^{a}
Mean	17.3^{b}	23.9^{a}	22.6^{a}	15.9^{b}	23.4^{a}	–

C – control, HA – humic acid, FYM – farmyard manure, FYM + HA – farmyard manure + humic acid, VC – vermicompost, VC + HA – vermicompost + humic acid, FNC – Fertil CN 40–12.5 , FCN + HA – Fertil CN 40 –12.5 + humic acid.

** I_0 – without irrigation; I_1 – drip irrigation

Different letters in the columns mean the significant difference (HSD) at $P < 0.05$

average tuber weight. However, a significant increase in the value of this trait was obtained on the irrigated objects. The increase in average tuber weight under drip irrigation in different fertilizer variants ranged from 5.1 g (8.5%) on the control object to 17.5 g (21.0%) after applying Fertil CN fertilizer. The highest average tuber weight was recorded in 2018, characterized by significantly higher rainfall in July, the period of intensive tuber weight gain, compared to potato needs. The smallest tuber weight, and at the same time the number of tubers set, was recorded in 2019, which was characterized by a very large rainfall deficit and high air temperature in June.

The number of tubers set ranged from 6.2 to 11.8, and depended on the type of fertilization, irrigation and the year of the study (tab. 3). On average, potato plants on irrigated objects set 6.3% more tubers than on non-irrigated objects. In the study by Mokh et al. [2015] the largest number of tubers were set by potato plants under field water capacity conditions, while under deficit irrigation the number of tubers was significantly lower. In the study, the largest increase in the number of tubers per plant under irrigation was found after the application of manure (8.5%), while the smallest increase in the number of tubers per plant was found on the control plot and after the application of HA (4.2%). The number of tubers set is determined by a number of factors, including soil and climatic conditions, cultivar characteristics, as well as the level of supply of potato plants with nutrients, mainly nitrogen [Kolodziejczyk 2014]. The results showed a significant effect of the type of fertilization applied on the value of this trait. The highest number of tubers was found after the application of Fertil CN fertilizer (9.0 pcs), significantly less on objects fertilized with manure and vermicompost, and the least after the application of humic acids (7.3 pcs). The combined application of HA with these fertilizers had no significant effect on the number of tubers set.

The share of marketable tuber fractions in the total yield on non-irrigated sites averaged 76.2%, while that of large tubers was 42.9% (tab. 3). The use of drip irrigation increased the share of these tuber fractions in total yield by 6.7% and 12.8%, respectively. In the study by Kołodziejczyk [2021] carried out in worse soil conditions (light clay), the increase in the share of the marketable and large tuber fractions in the total yield under irrigation was at a higher level and amounted to 9.1% and 30.1%, respectively. The highest increase in the share of the marketable tuber fraction under irrigation was found in the objects fertilized with vermicompost (7.3%), while the fraction of large tubers after the application of Fertil CN fertilizer and humic acids (14.0%). In general, the highest weight of marketable and large tubers was harvested on sites fertilized with Fertil CN, significantly less on sites fertilized with manure and vermicompost, and the least on the control site and after HA application. The weather conditions prevailing in 2020 had a favorable effect on the formation of the share of the marketable tuber fraction in the total yield despite the lowest amount of precipitation in the three-year cycle of the study and the lowest air temperature. In contrast, the largest share of large tubers was recorded in 2019 as a result of a small number of tubers set due to possibly excessively high air temperature during the tuberization period.

Table 3. Tuber yield structure

Fertilization	Irrigation		Year			Mean
	I_0	I_1	2018	2019	2020	
average tuber weight (g)						
C	59.9^{c}	65.0^{c}	65.8^{c}	54.8^{c}	66.9^{c}	62.5^{c}
HA	62.4^{c}	67.6^{c}	68.0^{c}	56.3^{c}	70.5^{c}	65.0^{c}
FYM	77.0^{b}	89.6^{b}	106.2^{b}	68.9^{b}	74.8^{bc}	83.3^{b}
FYM + HA	78.6^{b}	90.3^{b}	108.4^{b}	66.5^{b}	78.5^{b}	84.4^{b}
VC	77.3^{b}	90.1^{b}	109.8^{b}	66.0^{b}	75.4^{b}	83.7^{b}
VC + HA	76.0^{b}	90.3^{b}	108.4^{b}	65.6^{b}	75.4^{b}	83.1^{b}
FCN + HA	83.7^{a}	101.2^{a}	115.6^{a}	75.8^{a}	86.0^{a}	92.4^{a}
FCN + HA	83.5^{a}	101.0^{a}	115.8^{a}	75.0^{a}	86.0^{a}	92.2^{a}
Mean	74.8^{b}	86.9^{a}	99.7^{a}	66.1^{c}	76.7^{b}	–
number of tubers per plant (pcs.)						
C	7.1^{c}	7.4^{d}	7.1^{b}	6.2^{b}	8.4^{d}	7.2^{d}
HA	7.1^{c}	7.4^{d}	7.0^{b}	6.4^{b}	8.5^{d}	7.3^{d}
FYM	8.2^{b}	8.9^{b}	7.6^{a}	7.2^{a}	10.9^{b}	8.6^{b}
FYM + HA	8.3^{ab}	8.9^{b}	7.7^{a}	7.2^{a}	11.0^{b}	8.6^{b}
VC	8.0^{b}	8.4^{c}	7.7^{a}	7.1^{a}	9.8^{c}	8.2^{c}
VC + HA	8.1^{b}	8.7^{bc}	7.9^{a}	7.2^{a}	10.1^{c}	8.4^{c}
FCN	8.7^{a}	9.3^{a}	7.9^{a}	7.3^{a}	11.8^{a}	9.0^{a}
FCN + HA	8.7^{a}	9.2^{ab}	8.1^{a}	7.3^{a}	11.6^{a}	9.0^{a}
Mean	8.0^{b}	8.5^{a}	7.6^{b}	7.0^{c}	10.2^{a}	–
share of marketable tubers (%)						
C	65.1^{d}	69.0^{c}	63.9^{d}	66.6^{b}	70.6^{c}	67.0^{c}
HA	67.3^{c}	71.8^{c}	68.2^{c}	67.4^{b}	73.0^{c}	69.5^{c}
FYM	78.8^{b}	83.2^{b}	72.7^{b}	81.6^{a}	87.4^{b}	80.7^{b}
FYM + HA	78.3^{b}	84.2^{b}	72.0^{b}	82.8^{a}	88.2^{b}	81.1^{b}
VC	78.3^{b}	83.5^{b}	73.0^{b}	82.0^{a}	88.5^{b}	81.1^{b}
VC + HA	78.0^{b}	83.7^{b}	72.3^{b}	82.4^{a}	88.4^{b}	80.9^{b}
FCN	82.4^{ab}	87.5^{a}	78.8^{a}	83.0^{a}	91.9^{a}	84.7^{a}
FCN + HA	82.1^{a}	87.6^{a}	79.5^{a}	83.2^{a}	93.0^{a}	85.1^{a}
Mean	76.2^{b}	81.3^{a}	72.6^{c}	78.6^{b}	85.1^{a}	–
share of large tubers (%)						
C	27.4^{c}	30.2^{d}	26.5^{d}	26.0^{c}	33.9^{c}	28.8^{d}
HA	32.0^{b}	35.5^{c}	37.5^{c}	29.1^{c}	34.6^{bc}	33.7^{c}
FYM	47.0^{a}	51.2^{b}	44.5^{b}	63.3^{b}	38.9^{ab}	49.1^{b}
FYM + HA	47.0^{a}	51.9^{b}	45.4^{b}	63.5^{b}	38.9^{ab}	48.9^{b}
VC	46.9^{a}	51.5^{b}	45.4^{b}	65.0^{ab}	37.2^{abc}	49.2^{b}
VC + HA	47.4^{a}	52.3^{ab}	45.7^{b}	65.8^{ab}	38.1^{ab}	49.8^{b}
FCN	49.6^{a}	56.4^{a}	50.6^{a}	67.3^{a}	41.1^{a}	53.0^{a}
FCN + HA	49.3^{a}	56.2^{a}	50.9^{a}	66.3^{ab}	41.1^{a}	52.7^{a}
Mean	42.9^{b}	48.4^{a}	43.3^{b}	55.8^{a}	38.0^{c}	–

Explanation as in tab. 2.

Chemical composition of tubers

The chemical composition of potato tubers is determined by a number of factors, including genetic characteristics of cultivars, fertilization, protection and the course of weather conditions [Fontes et al. 2010, 2016]. The study conducted in 2018–2020 showed no effect of irrigation on the content of starch and nitrates (V) in potato tubers (tab. 4). However, a significant effect of this factor was found for total protein content. The application of supplemental drip irrigation resulted in a decrease in the content of this component in the range of 0.2 to 1.6 g kg^{-1}, the highest on the control site, after the application of humic acids and Fertil CN fertilizer.

Table 4. Chemical composition of tubers (fresh mass)

Fertilization	Irrigation		Year			Mean
	I_0	I_1	2018	2019	2020	
starch (g kg^{-1} FM)						
C	138^{ab}	141^{a}	141^{abc}	140^{a}	138^{a}	140^{a}
HA	138^{ab}	140^{a}	143^{ab}	137^{abc}	138^{a}	139^{a}
FYM	140^{a}	139^{ab}	143^{ab}	140^{a}	136^{a}	139^{a}
FYM + HA	138^{ab}	139^{ab}	141^{abc}	138^{a}	135^{a}	138^{ab}
VC	139^{ab}	138^{ab}	144^{a}	134^{bc}	137^{a}	139^{a}
VC + HA	138^{ab}	137^{ab}	142^{ab}	134^{c}	137^{a}	138^{ab}
FCN	137^{ab}	136^{b}	139^{bc}	136^{abc}	136^{a}	137^{b}
FCN + HA	137^{b}	137^{ab}	138^{c}	138^{ab}	134^{a}	137^{b}
Mean	138^{a}	139^{a}	141^{a}	137^{b}	136^{b}	–
protein (g kg^{-1} FM)						
C	18.7^{b}	17.3^{c}	18.8^{b}	19.4^{a}	15.7^{b}	17.9^{a}
HA	18.9^{b}	17.7^{bc}	19.0^{b}	20.4^{a}	15.8^{b}	18.4^{a}
FYM	19.7^{ab}	19.4^{abc}	20.6^{ab}	20.8^{a}	17.4^{ab}	19.6^{a}
FYM + HA	19.8^{ab}	19.8^{a}	20.7^{ab}	21.1^{a}	17.5^{ab}	19.8^{a}
VC	19.4^{ab}	19.7^{a}	22.0^{a}	19.8^{a}	16.9^{ab}	19.6^{a}
VC + HA	20.1^{ab}	19.9^{a}	22.4^{a}	20.4^{a}	17.1^{ab}	20.0^{a}
FCN	21.2^{a}	19.6^{a}	21.8^{a}	20.5^{a}	18.7^{a}	20.3^{a}
FCN + HA	21.1^{a}	19.6^{a}	22.2^{a}	19.9^{a}	18.9^{a}	20.3^{a}
Mean	19.9^{a}	19.1^{b}	20.9^{a}	20.3^{a}	17.3^{b}	–
nitrates (mg kg^{-1} FM)						
C	32.2^{c}	28.7^{b}	25.8^{c}	32.0^{b}	33.5^{b}	30.4^{b}
HA	32.2^{c}	30.0^{b}	27.5^{c}	33.3^{b}	32.5^{b}	31.1^{b}
FYM	35.3^{bc}	34.7^{ab}	32.5^{bc}	36.8^{b}	35.8^{b}	35.0^{b}
FYM + HA	34.7^{bc}	35.2^{a}	33.8^{bc}	36.3^{b}	34.8^{b}	34.9^{b}
VC	42.5^{ab}	41.8^{a}	45.0^{a}	41.5^{ab}	40.0^{ab}	42.2^{a}
VC + HA	41.3^{ab}	40.8^{a}	44.3^{ab}	40.0^{ab}	39.0^{ab}	41.1^{a}
FCN	44.8^{a}	41.3^{a}	35.3^{bc}	46.8^{a}	47.3^{a}	43.1^{a}
FCN + HA	47.0^{a}	42.2^{a}	37.3^{ab}	46.8^{a}	49.8^{a}	44.6^{a}
Mean	36.8^{a}	38.8^{a}	35.2^{b}	39.2^{a}	39.1^{a}	–

Explanation as in tab. 2

The study by Salih et al. [2018] showed a different relationship, i.e., increased starch and protein accumulation in tubers under irrigation or more rainfall. The chemical composition of tubers was modified to a greater extent by the type of fertilization applied than by irrigation. The most starch (13.8–14.0%) was contained in tubers harvested on the control, fertilized with humic acids, manure and vermicompost, and the least after the application of Fertil CN fertilizer, averaging 13.7%. A different relationship was found for nitrate (V) and total protein content. In each of the fertilizer variants evaluated, potato tubers accumulated a higher amount of these components than on the control object, but a significant increase in nitrate (V) content was recorded only after the application of vermicompost and Fertil CN fertilizer, while in the case of total protein the differences were not statistically confirmed in any fertilizer object. The course of weather conditions in particular growing periods significantly modified the chemical composition of tubers. The greatest amount of starch and total protein, and the least amount of nitrates (V) were contained in tubers harvested in 2018, characterized by the highest amount of rainfall in July in the three-year cycle of the study, significantly exceeding the rainfall needs of the potato in this growing season. The lowest starch and protein content and the highest nitrate content were found in tubers harvested in 2020, with a much lower amount of precipitation in August than in the corresponding period of the multi-year cycle, as well as a higher average air temperature.

Water use efficiency

Water use efficiency (WUE) averaged 72.4 kg mm^{-1} and ranged from 33.9 kg mm^{-1} to 119.5 kg mm^{-1} (tab. 5). The highest WUE value was found on the FCN + HA fertilizer site, and the lowest on the control. Humic acids increased water use efficiency in all fertilizer sites, but the differences were not statistically confirmed. During the three-year study period, the highest water productivity was recorded in 2020 (92.1 kg mm^{-1}), and the lowest in 2019 (46.1 kg mm^{-1}). The low water use efficiency in 2019 was associated with the highest evapotranspiration (Eta) in the three-year study cycle. Irrigation water use efficiency (IWUE) was in a very wide range from 24.5 to 123.8 kg mm^{-1} and averaged 72.7 kg mm^{-1}. Drip irrigation increased both total and marketable yield, as it stabilised the soil water potential in the root zone by eliminating short-term but critical soil water deficits during tuberisation and tuber weight gain. The additional moisture promoted nitrogen mineralisation, which accelerated tuber biomass accumulation [Satognon et al. 2021]. The study by Svoboda et al. [2020] further showed that more frequent irrigation cycles stimulate potato root development. The highest yield was obtained in the variant of combined application of irrigation and Fertil CN fertiliser, which demonstrates the synergistic effect of these two factors. The study indicates that WUE and IWUE values are comparable. Ati et al. [2012] and Mokh et al. [2015] showed a significantly higher value of IWUE than WUE, while in the study of Eissa [2018], the WUE index reached a higher value than IWUE. The highest water use efficiency was found after the application of Fertil CN fertilizer, while the lowest was found on the control and humic acid-fertilized sites. The combined application of HA and manure, vermicompost and Fertil CN had no significant effect on the value of IWUE. In contrast, Kołodziejczyk [2021] reported an increase in water use efficiency on sites with combined HA and manure application, as well as Fertil CN fertilizer. IWUE was significantly influenced by weather conditions in each year of the study. The highest irrigation water use efficiency, averaging 91.5 kg mm^{-1}, was found in

2018, characterized by the highest average air temperature in the study cycle, and the lowest in 2020, which in turn was characterized by the lowest average air temperature and the greatest precipitation deficit.

Table 5. Water use efficiency (kg mm^{-1})

Fertilization	Water use efficiency				Irrigation water use efficiency			
	year			mean	year			mean
	2018	2019	2020		2018	2019	2020	
C	46.3^{c}	33.9^{c}	61.8^{d}	47.3^{d}	24.5^{b}	35.5^{c}	29.1^{c}	29.7^{d}
HA	47.1^{c}	36.2^{c}	67.6^{d}	50.3^{d}	26.3^{b}	40.9^{c}	29.1^{c}	32.0^{d}
FYM	83.7^{b}	47.5^{b}	94.5^{bc}	75.2^{bc}	106.8^{a}	81.0^{b}	46.4^{b}	78.1^{c}
FYM + HA	86.6^{b}	48.9^{ab}	97.6^{b}	77.7^{b}	113.9^{a}	81.8^{b}	51.4^{b}	82.4^{bc}
VC	87.2^{b}	45.8^{b}	87.7^{c}	73.5^{c}	114.4^{a}	72.4^{b}	45.3^{b}	77.4^{b}
VC + HA	87.1^{b}	48.1^{ab}	90.9^{bc}	75.4^{bc}	116.9^{a}	78.1^{b}	50.2^{b}	81.6^{b}
FCN	95.2^{a}	53.9^{ab}	117.3^{a}	88.8^{a}	113.9^{a}	120.9^{a}	62.0^{a}	98.9^{a}
FCN + HA	97.4^{a}	54.8^{a}	119.5^{a}	90.6^{a}	115.2^{a}	123.8^{a}	64.3^{a}	101.1^{a}
Mean	78.8^{b}	46.1^{c}	92.1^{a}	–	91.5^{a}	79.3^{b}	47.2^{c}	–

Explanation as in tab. 2.

The potential for microbial fertilisation

Fertil CN, characterised by easily mineralising organic N, outperformed manure and vermicompost in terms of yield. Microbial inoculants can bridge this gap by accelerating the mineralisation of FYM and VC and increasing nutrient uptake from these slow-acting fertilisers. Lazcano and Domínguez [2011] showed that a combined application of vermicompost with a Bacillus biofertiliser raised potato yields to a level statistically similar to organic-mineral fertilisers. Furthermore, the increase in root density induced by rhizobacteria may act synergistically with applied drip irrigation, potentially raising IWUE beyond the observed range of 24.5–122.8 kg mm^{-1}.

CONCLUSIONS

1. Fertil CN had the highest yield-forming efficiency. Significantly higher total and marketable tuber yield after application of this fertilizer compared to fertilization with manure or vermicompost was the result of higher average tuber weight and number of tubers set.

2. Fertilizer variants evaluated in the study differentiated the amount of starch and nitrates (V) in potato tubers, but had no effect on total protein content. Fertil CN resulted in lower starch content and higher nitrate accumulation. Increased nitrate content in tubers was also found after the application of vermicompost.

3. The application of humic acids did not affect the size and structure of tuber yield, chemical composition of tubers and water use efficiency.

4. Synchronised release rates of assimilable nitrogen and timely irrigation are more important for maximising potato yields than total nitrogen application.

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Odporność odmian ziemniaka na niszczyka ziemniaczaka (*Ditylenchus destructor* Thorne) w warunkach polowych

Resistance of potato cultivars to potato rot nematode (*Ditylenchus destructor* Thorne) in field conditions

Abstrakt. Doświadczenie przeprowadzono w Instytucie Hodowli i Aklimatyzacji Roślin – Państwowym Instytucie Badawczym, w Oddziale w Bydgoszczy w trzech sezonach 2021/2022, 2022/2023 i 2023/2024. Celem eksperymentu była polowa ocena odporności dziewięciu jadalnych i siedmiu skrobiowych odmian ziemniaka na porażenie przez niszczyka ziemniaczaka (*Ditylenchus destructor* Thorne). Sadzeniaki ziemniaka zakażano sztucznie nicieniami i uprawiano w warunkach polowych w sposób konwencjonalny. Kontrolę stanowiły sadzeniaki ziemniaka nie zakażane nicieniami. Po zbiorze plonu wykonano ocenę ilościową plonu oraz dwukrotnie porażenia bulw potomnych przez nicienia (jesienią i wiosną). Bulwy wszystkich badanych odmian uległy porażeniu i charakteryzowały się gorszymi parametrami ilościowymi w porównaniu z kontrolą. Po zimowym przechowywaniu zakres porażenia wzrósł dla wszystkich badanych genotypów ziemniaka. Średnio większe nasilenie objawów obserwowano u odmian jadalnych niż skrobiowych. Spośród odmian jadalnych ziemniaka najmniej podatna na niszczyka ziemniaczaka okazała się odmiana Lawenda, spośród skrobiowych – Pokusa. Najbardziej porażone były bulwy jadalnej odmiany Otolia i skrobiowej odmiany Zuzanna.

Słowa kluczowe: nicienie wolnożyjące, niszczyk ziemniaczak (*Ditylenchus destructor* Thorne), sadzeniaki ziemniaka, odporność odmian

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WSTĘP

Ditylenchus destructor – niszczyk ziemniaczak to nicień wolnożyjący, który pasożytuje na roślinach wyższych. Występuje na wszystkich kontynentach, głównie w strefie klimatu umiarkowanego [EPPO global database]. Spośród ponad stu gatunków roślin żywicielskich dla *D. destructor*, do tych o największym znaczeniu gospodarczym zalicza się zaledwie kilka gatunków uprawnych i ozdobnych: *Solanum tuberosum*, *Iris* spp., *Tulipa* spp., *Dahlia* spp., *Gladiolus* spp., *Rheum rhabarbarum*, *Trifolium* spp., *Daucus carota* oraz chwastów [Stefan 1997, Jeszke i in. 2014, PM 7/87 (2) 2017, Chen i in. 2020]. Niszczyk ziemniaczak przez wiele lat znajdował się na liście B w wykazie „Organizmy szkodliwe dla roślin i produktów roślinnych podlegające obowiązkowi zwalczania w wypadku stwierdzenia ich występowania na określonych roślinach lub produktach roślinnych", w tym w sadzeniakach ziemniaka. Podczas Panelu Plant Health EFSA w 2016 r. została przeprowadzona ocena zagrożenia fitosanitarnego tym agrofagiem na terytorium UE. Głównymi drogami wprowadzania i rozprzestrzeniania się tego nicienia na obszarze UE są rośliny przeznaczone do sadzenia, w tym sadzeniaki ziemniaka i cebulki kwiatowe. Od 2019 r. *D. destructor* znajduje się na liście regulowanych agrofagów niekwarantannowych sadzeniaków ziemniaka. Jego obecność we wszystkich kategoriach i klasach sadzeniaków jest niedozwolona [Jeger i in. 2016, Rozporządzenie Ministra Rolnictwa i Rozwoju Wsi z dnia 27 maja 2020 r., Rozporządzenie wykonawcze Komisji (UE) 2021/2285 z dnia 14 grudnia 2021 r.]. Dawniej na obszarze Polski funkcjonowały Stacje Oceny Sadzeniaków Ziemniaka (SOSZ) jako wyspecjalizowane jednostki kontrolne, odpowiadały za kwalifikację oraz ocenę jakości sadzeniaków. Badania dotyczące obecności niszczyka ziemniaczaka w kwalifikowanym materiale sadzeniakowym ziemniaka prowadziła Stefan [1999]. Jako materiał badawczy do analiz wykorzystała próby bulw pobrane z 15 jednostek SOSZ. Odsetek bulw zasiedlonych szkodnikiem zależał od stopnia kwalifikacji sadzeniaków, jedynie w kategorii najwyższej – super elita – nicienie nie występowały. W kolejnych klasach średni odsetek porażenia bulw wynosił: 0,7% dla kategorii elita, 0,8% dla oryginału i aż 2,0% dla sadzeniaków klasy A [Stefan 1999]. W wyniku reorganizacji systemu oceny sadzeniaków, stacje SOSZ zostały zlikwidowane, a ich kompetencje przejęła Państwowa Inspekcja Ochrony Roślin i Nasiennictwa (PIORiN), przy współpracy z COBORU w zakresie badań odmianowych [Ustawa z dnia 9 listopada 2012 r. o nasiennictwie]. W latach 2010–2022 również PIORiN prowadził monitoring kwalifikowanego materiału sadzeniakowego ziemniaka pod kątem obecności *D. destructor*. Wśród przebadanych 71 911 próbek bulw, niszczyka ziemniaczaka wykryto w 0,15% próbek, co świadczy o niskim poziomie jego występowania [Karnkowski i Guenter 2018, 2024].

Szkodliwość nicienia w uprawie ziemniaka polega na obniżeniu jego wartości towarowej i nasiennej oraz bezpośrednich stratach w plonie bulw, które wzrastają w okresie zimowego przechowywania. Na wielkość strat wpływa szereg czynników, takich jak: sprzyjające warunki atmosferyczne, struktura gleby, presja szkodnika, odmiana i termin sadzenia bulw. Czynniki te w różnym stopniu wpływają na wielkość spadku plonu w poszczególnych systemach uprawy [Ivaniuk 2003, Vovlas i in. 2005, Jones i in. 2013]. Straty w całkowitym plonie ziemniaków po zbiorze mogą sięgać 40% [Stefan 1995, Yan i in. 2023]. Nicień żeruje w częściach podziemnych roślin ziemniaka jak korzenie, bulwy i stolony. W Europie o szkodliwości niszczyka ziemniaczaka decydują przede wszystkim warunki glebowe i temperaturowe. Nie stanowi on zagrożenia dla regionów o zbyt wysokiej temperaturze i w miejscach, gdzie następuje znaczne przesuszanie gleby [Sturhan i Brzeski 1991]. Odpowiednia wilgotność i temperatura sprzyjają przyspieszeniu cyklu rozwojowego, co umożliwia rozwój większej liczby pokoleń szkodnika w trakcie jednego sezonu wegetacyjnego.

Objawy żerowania niszczyka ziemniaczaka nie są trudne do rozpoznania. Pierwsze oznaki żerowania w bulwach widoczne są po delikatnym usunięciu skórki jako małe białe punkty (ukryta forma porażenia). Skórka w tych miejscach jest lekko zapadnięta, łatwa do oddzielenia, z czasem z wyraźnymi typowymi zmarszczeniami i pęknięciami. Stopniowo plamy stają się szaro-ołowiane, pogłębiają się i obejmują coraz większy obszar widoczny na powierzchni bulwy. Skórka wysycha, pęka, a miąższ staje się gąbczasty i ciemnieje (ryc. 1). Poprzez uszkodzoną skórkę wnikają nicienie saprofityczne, grzyby, bakterie i roztocza powodujące rozwój wtórnych infekcji. Podczas zimowego przechowywania ziemniaków porażenie wzrasta, ponieważ nicienie przemieszczają się i zasiedlają sąsiednie bulwy. Wewnątrz bulw następuje szereg zmian fizjologicznych i biochemicznych, jak: zmniejszenie zawartości wody i skrobi, nadmierne gromadzenie cukrów, intensyfikacja lub redukcja procesów enzymatycznych, rozkład i zmiany ilościowe białek i aminokwasów. Przechowywanie silnie porażonych bulw może prowadzić nawet do utraty całego plonu [Stefan 1995, Hofmann i in. 2008, Bernard i in. 2017, Melnic i in. 2024].

Ryc. 1. Objawy porażenia bulwy ziemniaka przez niszczyka ziemniaczaka *D. destructor* Thorne (fot. K. Franke)
Fig. 1. Potato rot nematode *D. destructor* Thorne symptoms on potato (photo by K. Franke)

Rośliny ziemniaka słabo porażone przez niszczyka ziemniaczaka podczas okresu wegetacji mogą nie różnić się od zdrowych. W przypadku silnego porażenia rośliny wykazują znacznie zaburzony lub całkowicie zahamowany wzrost, stają się osłabione, więdną, żółkną, nierzadko obumierają. W obrębie jednego gatunku występują rośliny bardziej lub mniej podatne na porażenie przez nicienia. Uprawa odpornych odmian roślin stanowi sprawdzoną metodę stosowaną w walce z nicieniami. Stosowanie przed laty tylko odpornych odmian ziemniaka na *Globodera rostochiensis* pozwoliło na ograniczenie występowania tego kwarantannowego nicienia na terenie kraju [Malec 1980, Przetakiewicz 2019]. Obecnie odmiany ziemniaka odporne na mątwika ziemniaczanego stanową ponad 95% wszystkich odmian wpisanych do Krajowego Rejestru Odmian [Franke i in. 2019]. Odporność odmian ziemniaka na porażenie przez *D. destructor* nie jest stałym elementem ich charakterystyki. Wcześniejsze doniesienia literaturowe dokumentowały jednak zróżnicowaną reakcję odmian ziemniaka na szkodnika [Stefan 1980, Malinowska i Kowalska 2006, Franke i Malinowska 2007]. Dostępne informacje są ograniczone i nieaktualne. Badania te prowadzono dawno i niewielki odsetek z testowanych odmian jest dostępny obecnie w uprawie. Szkodliwość niszczyka ziemniaczaka wzrasta w warunkach nawadniania pól szczególnie w uprawie ziemniaków przeznaczonych do przemysłu skrobiowego. Ziemniak jadalny uprawiany na mniejszą skalę często bez zachowania racjonalnego zmianowania sprzyja nasileniu występowania chwastów, szkodników i patogenów [Marks i in. 2018, Pridannikov 2022]. Fragmenty roślin i bulwy pozostawione na polu stanowią źródło porażenia w kolejnym roku uprawy.

Nie ma skutecznej metody ochrony przed niszczykiem ziemniaczakiem, nie jest również prowadzona w tym kierunku hodowla odpornościowa. Ocena podatności ziemniaków na tego nicienia na terenie kraju może być ważnym wyznacznikiem wyboru odmiany do uprawy w warunkach dużej presji szkodnika. Zamysłem prezentowanych wyników badań była ocena różnic porażenia przez niszczyka ziemniaczaka wybranych jadalnych i skrobiowych odmian ziemniaka. Podczas przeprowadzonego trzyletniego eksperymentu polowego w latach 2021/2022–2023/2024 sadzono sztucznie zakażane sadzeniaki 16 odmian ziemniaka i oceniano dwukrotnie wielkość porażenia bulw potomnych: jesienią i wiosną, a także różnice w ocenie ilościowej uzyskanego plonu.

MATERIAŁ I METODY

Doświadczenie prowadzono w latach 2021/2022, 2022/2023 i 2023/2024 w Instytucie Hodowli i Aklimatyzacji Roślin – Państwowym Instytucie Badawczym, w Oddziale w Bydgoszczy. Do badań wykorzystano zdrowy materiał sadzeniakowy 16 odmian ziemniaka oraz bulwy ziemniaka porażone przez *D. destructor*. Wybrano odmiany o różnej wczesności, przeznaczeniu i pochodzeniu (hodowle krajowe i zagraniczne). Listę wybranych odmian ziemniaka przedstawiono w tabeli 1. Dla każdej odmiany sadzono 9 bulw sztucznie zakażanych nicieniami oraz trzy zdrowe stanowiące kontrolę. Źródłem porażenia były rozdrobnione fragmenty bulw porażonych nicieniami (w różnych stadiach rozwoju), umieszczone w niewielkich nacięciach pod powierzchnią skórki sadzeniaka. Wielkość inokulum określono na poziomie ok. 5000 osobników w różnych stadiach rozwojowych na jedną bulwę. Ziemniaki uprawiano w sposób konwencjonalny, stosując mechaniczne metody ochrony przed zachwaszczeniem, a także chemiczną ochronę przed stonką ziemniaczaną i zarazą ziemniaka. Prowadzono obserwacje wschodów i wzrostu roślin. Po zbiorze liczono i ważono bulwy zebrane dla każdej rośliny oddzielnie. Wielkość porażenia bulw potomnych określono dwukrotnie: miesiąc po zbiorze oraz po zimowym przechowaniu. Oceniano wielkość zewnętrznych objawów na każdej bulwie osobno według skali: 0 – brak objawów, 1 – do 0,5% powierzchni bulwy, 2 – od 0,6% do 20% powierzchni bulwy, 3 – od 21% do 50% powierzchni bulwy, 4 – od 51% do 70% powierzchni bulwy, 5 – ponad 70% powierzchni bulwy.

Tabela 1. Charakterystyka odmian ziemniaka
Table 1. Potato varieties characteristic

Odmiana Cultivar	Przeznaczenie Market outlet	Wczesność Maturity	Hodowca Potato Breeding Station
Amarant	skrobiowa/starchy	średniopóźna/ mid-late	PMHZ sp. z o.o. Strzekęcino
Bila	jadalna/edible	wczesna/early	HZ Zamarte
Denar	jadalna/edible	bardzo wczesna/ very early	HZ Zamarte
Desiree	jadalna/edible	bardzo wczesna/ very early	HZPC Holland BV
Inwestor	skrobiowa/starchy	późna/late	PMHZ sp. z o.o. Strzekęcino
Irys	jadalna/edible	bardzo wczesna/ very early	PMHZ sp. z o.o. Strzekęcino
Jasia	skrobiowa/starchy	późna/late	HZ Zamarte
Lawenda	jadalna/edible	wczesna/early	HZ Zamarte
Longina	jadalna/edible	wczesna/early	HZ Zamarte
Malaga	jadalna/edible	średniowczesna/ mid-early	HZ Zamarte
Mieszko	skrobiowa/starchy	średniowczesna/ mid-early	PMHZ sp. z o.o. Strzekęcino
Otolia	jadalna/edible	średniowczesna/ mid-early	Europlant
Pokusa	skrobiowa/starchy	późna/late	PMHZ sp. z o.o. Strzekęcino
Szyper	skrobiowa/starchy	średniowczesna/ mid-early	PMHZ sp. z o.o. Strzekęcino
Vineta	jadalna/edible	wczesna/early	Europlant
Zuzanna	skrobiowa/starchy	średniowczesna/ mid-early	Europlant

* – wartości różnią się istotnie statystycznie na poziomie $p < 0{,}05$/ values differ significantly at the level of $p < 0.05$

Na podstawie wyników obserwacji porażenia bulw określano indeks porażenia zgodnie ze wzorem Towsenda-Heubergera [Ginter 1981]:

$$\%\ \text{porażenia} = \left(\frac{\sum_0^{i}(n \times v)}{iN}\right) \times 100$$

gdzie: v – stopień porażenia, i – najwyższy stopień porażenia, n – liczba bulw w stopniu, N – całkowita liczba badanych bulw.

Ocenę statystyczną wykonano przy pomocy programu STATISTICA. Normalność rozkładu danych oceniano przy pomocy testu Shapiro–Wilka. Istotność różnic pomiędzy parametrami weryfikowano przy pomocy testu t-Studenta na poziomie istotności równym 0,05.

WYNIKI

Podczas sezonu wegetacyjnego prowadzono dziennik obserwacji polowych. Zaobserwowano równomierne wschody oraz brak wyraźnych różnic w pokroju roślin pomiędzy porażonymi przez niszczyka ziemniaczaka i zdrowymi w obrębie każdej odmiany.

Ocena ilościowa plonu

Po zbiorze plonu bulwy ważono i liczono. Wartości parametrów zestawiono i poddano ocenie statystycznej (tab. 2). W badaniach wykazano istotne różnice w wartościach ocenianych parametrów dla poszczególnych odmian, a także pomiędzy bulwami potomnymi zebranymi spod roślin porażonych przez niszczyka ziemniaczaka i zdrowych. Waga bulw pochodzących z obiektów kontrolnych była wyższa dla wszystkich badanych odmian.

Tabela 2. Różnice w wagach i liczbie bulw porażonych przez *D. destructor* w odniesieniu do zdrowych
Table 2. Differences in weight and number of tubers infected by *D. destructor* in relation to healthy ones

Odmiana Cultivar	Różnice w wadze bulw (%) Differences in the weight of tubers (%)	Różnice w liczbie bulw (%) Differences in the number of tubers (%)
odmiany jadalne/ edible cultivars		
Bila	–32,6*	–7,6
Denar	–29,5*	–10,0*
Desiree	–21,8*	–7,1*
Irys	–39,2*	–10,1
Lawenda	–40,2*	–9,0
Longina	–37,6*	–6,5*
Malaga	–38,6*	+8,7
Otolia	–38,4*	–6,5
Vineta	–36,5*	–7,1*
Średnia	–34,9	–6,1
odmiany skrobiowe/ starchy cultivars		
Amarant	–13,1	–7,9
Inwestor	–33,0*	–8,5*
Jasia	–31,4*	–9,1
Mieszko	–19,3*	+13,1*
Pokusa	–37,7*	–9,3
Szyper	–36,2*	+8,6
Zuzanna	–20,4*	–6,5*
Średnia	–27,3	–2,8

* wartości różnią się istotnie statystycznie na poziomie $p < 0,05$/ values differ significantly at the level of $p < 0.05$

W grupie odmian jadalnych straty w plonie były większe i wynosiły średnio 34,9%. Największe różnice w wielkości plonu zanotowano dla odmiany Lawenda – aż o 40,2%, następnie dla odmiany Irys – 39,1%, Malaga – 38,6% i Otolia – 38,4%. Najmniejsze różnice zaobserwowano u odmiany Desiree o 21,8%. U odmian skrobiowych średni spadek plonu oszacowano na poziomie niższym, średnio o 27,3%, największy u odmian Pokusa i Szyper, odpowiednio o 37,7% i 36,2%, a najmniejszy dla odmiany Amarant, o 13,1%. W ocenie statystycznej średnia waga bulw porażonych była istotnie mniejsza niż zdrowych ($p < 0.05$) dla większości odmian.

Dla 13 spośród ocenianych odmian wykazano tendencję do mniejszej liczby bulw spod roślin porażonych niż zdrowych, ale nie zawsze różnice te były istotne statystycznie (tab. 2). Istotność różnic ($p < 0.05$) udowodniono dla odmian Denar, Desiree, Longina, Vineta i Zuzanna. Dla niektórych odmian (Otolia i Pokusa) różnice nie były istotne ze względu na dużą zmienność ocenianego parametru w kolejnych latach badań. U pozostałych odmian (Malaga, Mieszko i Szyper) nie wystąpiła podobna tendencja, zaobserwowano natomiast tzw. zdrobnienie bulw.

Porażenie bulw przez *D. destructor*

Ocena porażenia bulw potomnych przez niszczyka ziemniaczaka została wykonana w każdym roku badań dwukrotnie, jesienią – jeden miesiąc po zbiorze oraz wiosną – po okresie zimowego przechowywania. Bulwy zebrane z obiektów kontrolnych nie uległy porażeniu. Dla bulw zebranych spod roślin porażonych wyniki uśredniono i przedstawiono w tabeli 3. Wszystkie badane odmiany uległy porażeniu, jednak nasilenie objawów nie było równomierne. W jesiennej ocenie najmniejsze średnie porażenie obserwowano dla odmiany skrobiowej Pokusa – 2,8% oraz jadalnej Lawenda – 3,2%. Najbardziej podatne na porażenie przez niszczyka ziemniaczaka okazały się odmiany jadalne Otolia (35,3%) i Denar (32,0%). Wykazano istotne statystycznie różnice w zmianach porażenia bulw po zimowym ich przechowaniu dla wszystkich badanych genotypów ziemniaka. Po zimowym przechowywaniu zwiększył się obszar powierzchni bulw z wyraźnymi objawami bytowania w nich nicieni, a najwyższe porażenie odnotowano dla odmian jadalnych Otolia (63,5%), następnie Denar (44,7%) i Irys (39,9%). U odmian skrobiowych średnia wielkość porażenia była niższa. Najmniejsze porażenie charakteryzowało odmiany Lawenda – 4,4% i Pokusa – 6,0 %, a najwyższe odmianę Zuzanna – 31,4%.

W ocenie jesiennej plonu, objawy bytowania nicieni widoczne były w okolicy przystolonowej, co potwierdzają szczegółowe badania Stefan [1979], w których wykazuje, że źródło porażenia stanowiły zainfekowane sadzeniaki, a nicienie migrowały w roślinie do bulw potomnych. Po zimowym przechowywaniu oprócz większego udziału bulw porażonych w plonie całkowitym wzrastał udział tych z wyższym stopniem porażenia. Oprócz wcześniejszych objawy występowały również w części bocznej i wierzchołkowej bulw, co dowodzi natomiast migracji nicieni do bulw sąsiednich. Odsetek bulw porażonych wzrósł najbardziej u dwóch odmian jadalnych – Otolia (o 28,2%) i Irys (o 17,9%) oraz skrobiowej – Zuzanna (o 14,6%). Wzrost zakresu porażenia bulw odzwierciedlają wartości współczynnika Towsenda-Haubergera (tab. 3). Najwyższy wzrost indeksu porażenia miał miejsce u trzech odmian jadalnych: Otolia, Desiree i Denar, odpowiednio o 22,3%, 22,3% i 20,9%. Najniższe wartości porażenia w wiosennej ocenie stwierdzono dla odmian skrobiowych Pokusa – 2,6% i Szyper 4,9% oraz jadalnej odmiany Lawenda – 2,7%. Spośród ocenianych odmian najmniej podatne okazały się dwie odmiany Pokusa i Lawenda, które charakteryzował najmniejszy odsetek bulw porażonych w obu terminach oceny i najniższe zmiany w indeksie porażenia, znaczny natomiast spadek plonu w porównaniu do bulw zdrowych.

Tabela 3. Porażenie bulw ziemniaka przez *D. destructor* w okresie jesień 2021–wiosna 2024 oceniane w dwóch terminach: po zbiorze (jesień) i po okresie przechowywania (wiosna) w 5-stopniowej skali

Table 3. Potato tubers infected by *D. destructor* in the period autumn 2021–spring 2024 assessed in two terms: after harvest (autumn) and after storage (spring) performed on a 5-degree scale

Odmiany Cultivars		Indeks porażenia wg Towsenda-Haubergera Towsend-Hauberger infection index		Odsetek bulw ziemniaka porażonych przez *D. destructor* Percentage of tubers infected by *D. destructor*											
				jesień/autumn						wiosna/spring					
		jesień/autumn	wiosna/spring	1[#]	2	3	4	5	łącznie/total	1[#]	2	3	4	5	łącznie/total
Jadalne Edible	Bila	3,2	6,7	0,8	1,3	3,0	0,4	0,4	5,9	1,3	3,8	1,7	3,8	0,8	11,4*
	Denar	9,4	30,3	12,2	13,2	2,5	4,1	0,0	32,0	3,4	9,2	9,2	12,6	10,3	44,7*
	Desiree	5,9	28,2	2,8	3,7	2,8	1,9	1,9	7,3	9,7	10,2	7,9	6,5	7,4	17,1*
	Irys	10,1	27,9	5,1	8,4	5,5	2,6	0,4	22,0	4,4	5,9	7,0	10,4	12,2	39,9*
	Lawenda	0,9	2,7	2,4	0,0	0,8	0,0	0,0	3,2	0,0	1,6	1,2	1,2	0,4	4,4*
	Longina	2,0	6,7	2,3	4,0	0,0	0,0	0,0	6,3	1,7	4,0	2,3	0,0	3,4	11,4*
	Malaga	1,6	6,4	3,9	1,9	0,0	0,0	0,1	5,9	5,6	2,6	3,0	2,8	0,2	14,2*
	Otolia	24,5	46,8	1,2	7,6	10,0	6,5	10,0	35,3	4,7	6,5	12,3	20,6	19,4	63,5*
	Vineta	8,1	20,0	4,3	8,5	3,6	0,6	1,2	18,2	4,3	2,6	6,3	5,8	9,5	28,5*
Skrobiowe Starchy	Amarant	3,2	8,0	2,2	3,6	2,1	0,0	0,0	7,9	4,7	4,2	4,2	2,3	1,4	16,8*
	Inwestor	2,4	6,8	1,4	1,7	1,3	0,0	0,6	5,0	2,7	3,6	0,2	3,4	1,9	11,8*
	Jasia	5,8	14,2	3,0	3,4	2,2	0,4	2,2	11,2	2,2	3,7	6,4	4,9	4,5	21,7*
	Mieszko	2,4	5,6	3,0	1,4	1,1	0,8	0,0	6,3	0,8	3,0	1,4	1,6	2,2	9,0*
	Pokusa	0,9	2,6	1,2	1,6	0,0	0,0	0,0	2,8	0,8	3,6	1,2	0,4	0,0	6,0*
	Szyper	1,8	4,9	3,0	1,7	0,9	0,0	0,0	5,6	2,6	1,7	2,6	2,2	0,4	9,5*
	Zuzanna	6,4	20,3	8,1	4,6	2,9	0,0	1,2	16,8	2,5	10,0	4,6	7,5	6,8	31,4*

[#] Skala oceny porażenia bulw w stopniach: 1: do 0,5% powierzchni bulwy, 2: 0,6–20%, 3: 21–50%, 4: 21–50%, 5: ponad 70%/ Tuber infection assessment scale in degrees: 1: up to 0.5% of tuber surface, 2: 0.6–20%, 3: 21–50%, 4: 21–50%, 5: over 70%

* Wartości różnią się istotnie statystycznie na poziomie $p < 0,05$/ Values differ significantly at the level of $p < 0$

DYSKUSJA

Ocena ilościowa plonu

Wszystkie rośliny niezależnie od cechy odporności są narażone na inwazję agrofagów. W przypadku odmian odpornych nicienie po wniknięciu do rośliny nie mogą się dalej rozwijać i giną. Samo żerowanie nicieni na odpornych roślinach może powodować zahamowanie rozwoju, a ograniczona powierzchnia asymilacyjna i gorsza kondycja roślin powodują spadek plonu [Brzeski 1992]. Dane literaturowe potwierdzają wpływ żerowania niszczyka ziemniaczaka na spadek plonu ziemniaka [Stefan 1995]. W badaniach własnych, a także u Mwaura i in. [2015b] spadek plonu bulw kształtował się na różnym poziomie dla poszczególnych odmian i nie zależał od wielkości porażenia zewnętrznego i wewnętrznego bulw. W innym badaniu porażenie *D. destructor* nie miało wpływu na liczbę bulw, a jedynie na masę bulw tylko przy wysokim poziomie inokulum [Mwaura i in. 2015a]. U odmiany Spunta autorzy nie obserwowali zewnętrznych ani wewnętrznych objawów uszkodzenia, jednak masa bulw była niższa o 28% w odniesieniu do kontroli. Odmiany Bintje i Innovator zostały sklasyfikowane jako odmiany tolerancyjne, ze względu na nieznaczną utratą masy bulw i zakres uszkodzeń zewnętrznych.

Porażenie bulw przez *D. destructor*

Pierwsze wzmianki literaturowe dotyczące badań nad odpornością ziemniaka na porażenie przez niszczyka ziemniaczaka sięgają lat 20. i 30. XX w. [Moore 1971]. Na terenie kraju doświadczenia w zakresie szkodliwości, biologii i odporności roślin na niszczyka ziemniaczaka prowadziła Stefan [1979]. Badaniami objęła m.in. 800 odmian i 327 rodów hodowlanych ziemniaka oraz 150 genotypów należących do 27 innych gatunków z rodzaju *Solanum*. Na podstawie uzyskanych wyników oceny porażenia bulw autorka sklasyfikowała badane genotypy w pięciu grupach podatności. Nie stwierdziła żadnej odpornej odmiany ziemniaka. W grupie odmian bardzo słabo podatnych wymieniła tylko pięć: Belg, Grom, Pimpernel, Robijn i Rode Star. Wśród dzikich gatunków uzyskała bardziej obiecujące wyniki. Rośliny *S. commersonii, S. pinnatisectum, S. demissum, S. stoloniferum, S. curtilobum, S. chomatophilum, S. cardiophyllum, S. chacoense* i *S. spegazzinii* nie uległy porażeniu przez niszczyka ziemniaczaka. Kolejne doświadczenia na terenie kraju dotyczące odporności odmian ziemniaka prowadzono w latach 2001–2003 oraz 2005–2007. Nie zaobserwowano odmian całkowicie odpornych. Wśród 34 badanych, jako najmniej porażone wskazano odmiany Dunajec i Aster [Malinowska i Kowalska 2006, Franke i Malinowska 2007].

Badania dotyczące odporności ziemniaka na porażenie przez *D. destructor* prowadzono również poza granicami kraju. Mwaura i in. [2015b] oraz Ryabtseva [2018] wyróżnili odmiany bardziej wrażliwe oraz bardziej odporne na porażenie przez *D. destructor*. Wśród tych ostatnich autorzy wymienili odmiany Achilles, Adretta, Darwina, Feztien, Fresco, Hansa, Hela, Laura, Orfei, Santé, Memphis, Panther, Red Scarlett. Natomiast Shesteperov i Volodin [2023] do odmian słabo podatnych zaliczyli dwie: Vinetę i Colette.

W Bułgarii, Samaliev i Markova [2015] prowadzili ocenę podatności odmian na niszczyka ziemniaczaka, m.in. kierując się standardami EPPO dotyczącymi klasyfikacji odporności odmian ziemniaka na *Globodera* spp. [European and Mediterranean Plant Protection Organization 2006]. Na podstawie uzyskanych wyników odmianę Innovator określono jako odporną, a pozostałe jako podatne. W eksperymencie *Ditylenchus destructor* spowodował znaczne uszkodzenia bulw ziemniaka. Procent uszkodzeń zewnętrznych i wewnętrznych oszacowano na poziomie odpowiednio od 0–38,5% i 0–19%. Orfei i Sante były najmniej porażonymi odmianami. Natomiast odmiana Spunta ze względu na brak objawów, mimo obecności nicieni w bulwach, została określona jako porażona bezobjawowo. Mwaura i in. [2015a] również zastosowali metodykę badań opartą o te same standardy EPPO i odmianę ziemniaka Desiree wybrali jako standardową kontrolę podatną. Do badań własnych również wybrano tę odmianę. Była jedną z bardziej porażonych, jednak dla odmiany Otolia wartości parametrów oceny porażenia były wyższe. W prowadzonych badaniach szukano m.in. uzasadnienia w zmienności porażenia odmian ziemniaka przez niszczyka ziemniaczaka. Zdaniem Chen i in. [2020] u odmian skrobiowych o dłuższym okresie wegetacji i przy sprzyjających warunkach do rozwoju nicieni oraz ich krótkich cyklach życiowych może nastąpić szybki wzrost populacji nicieni, co może doprowadzić do wzrostu uszkodzenia bulw ziemniaka. Hermeziu i in. [2021] zauważyli natomiast, że w niekorzystnych warunkach do rozwoju szkodnika podatne odmiany ziemniaka mogą nie ulec porażeniu. Ivanyuk [2003] zaobserwował mniejsze porażenie bulw uprawianych na glebach piaszczysto-gliniastych, co tłumaczy niekorzystnymi warunkami pogodowymi w okresie wegetacji, szczególnie niższymi opadami. Wyniki badań własnych nie potwierdzają wszystkich danych literaturowych. Okres wegetacji badanych genotypów ziemniaka był zbliżony, uprawiano je w jednakowych warunkach glebowych i pogodowych. Desiree należy do grupy odmian jadalnych i to właśnie odmiany jadalne uległy większemu porażeniu przez niszczyka ziemniaczaka.

Ograniczanie rozwoju *D. destructor* poprzez płodozmian nie jest w pełni możliwe ze względu na szeroki zakres żywicieli szkodnika. W warunkach zmian klimatu, organizacji uprawy ziemniaka ukierunkowanej na produkt o konkretnym przeznaczeniu, konieczności wprowadzania nawadniania ziemniaka nicień stanowić będzie poważne zagrożenie dla wydajności uprawy i jakości bulw. Uprawa odmian odpornych stanowi efektywną, opłacalną i bezpieczną dla środowiska metodę ochrony przed niszczykiem ziemniaczakiem. Zagadnienie odporności odmian ziemniaka na niszczyka ziemniaczaka stanowi ciekawy kierunek badań.

WNIOSKI

1. Uprawa sadzeniaków porażonych przez *D. destructor* powoduje spadek plonu bulw.
2. Spośród badanych odmian jadalnych i skrobiowych nie stwierdzono odpornej na porażenie przez niszczyka ziemniaczaka.
3. Podczas zimowego przechowywania wielkość porażenia bulw powodowana przez nicienie wzrastała nawet dwukrotnie.
4. W trzyletniej ocenie ziemniaka najmniej podatne na porażenie przez niszczyka ziemniaczaka były odmiany Lawenda i Pokusa.

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Źródło finansowania: Badania sfinansowano z dotacji na utrzymanie potencjału badawczego.

Abstract. The field experiment was conducted in The Plant Breeding and Acclimatization Institute – National Research Institute, Bydgoszcz Division. in three seasons in 2021/2022, 2022/2023 and 2023/2024. The aim of the experiment was to evaluate in the field the impact of potato pest of 9 edible and 7 starch potato cultivars to infection by the potato rot nematode (*Ditylenchus destructor* Thorne). Seed potatoes were infected with nematodes and grown conventionally in field conditions. The control consisted of seed potatoes not infected with nematodes. After harvesting, the following assessments were carried out: quantitative assessment of the yield and two external infections of the daughter tubers by the potato rot nematode (in autumn and spring). Tubers of all tested cultivars were infected and had worse quantitative parameters compared to the control. After winter storage of tubers, the extent of infection increased for all tested cultivars. Edible cultivars were more susceptible to nematode infection than starch cultivars. Among the edible cultivars, the least susceptible to the potato rot was the Lavender cultivar, and among the starch cultivars – Pokusa. The most infected cultivars were Otolia (edible) and Zuzanna (starch).

Keywords: free living nematodes, *Ditylenchus destructor* Thorne, potato rot nematode, seed potatoes, variety resistance

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AHP-based site suitability for agrivoltaics in Lublin Voivodeship, Poland

Ocena przydatności terenów dla agrowoltaiki w województwie lubelskim z wykorzystaniem metody AHP

Abstract. In Poland, as in the global energy market, the popularity of renewable energy sources, whose main advantage over fossil fuels is climate neutrality, is growing. An alternative to dedicating land exclusively to renewable energy is agrivoltaics, which involves dual use of land: for agricultural production and for photovoltaic installations that convert solar energy into usable energy simultaneously. The study's main purpose was to answer two questions: to what extent are the agricultural lands of eastern Poland suitable for the development of agrivoltaics, and how does the selection of criteria affect the final result of the analysis in light of the Analytic Hierarchy Process. The study area was the Lublin Voivodeship, whose potential was evaluated based on 8 orography and land use criteria. The study focuses on spatial conditions, whereas legal and economic conditions have not been considered. The analysis showed that implementing agrivoltaics is theoretically feasible on 79% of the Voivodeship's total agricultural land, of which 9,961 km^2 can be considered at least moderately highly suitable. Additionally, two alternative scenarios were analysed: in the first, only orography criteria were assessed, and in the second, only land use. The comparative analysis revealed that the choice of criteria significantly impacts the results. The highest area suitability was obtained in the assessment considering land use only, and the lowest for orography.

Keywords: agrivoltaics, renewable energy, photovoltaics, Poland, land suitability

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INTRODUCTION

The progressive exploitation of fossil fuels, leading to the gradual depletion of their resources, and the lack of climate neutrality are the two main problems associated with obtaining energy via non-renewable sources from the point of view of the global energy market. The counterweight to fossil fuels is renewable energy, characterised by its recoverability and lack of negative impact on climate change. In recent years, a successive increase in the importance of renewable energy sources in the global energy market has been observed, manifesting in both an increase in generating capacity and energy consumption [IEA et al. 2023, IEA 2024]. The main contributor to the development of renewable energy globally is Europe, where the share of renewable energy in the total generation potential in 2022 was 35%, which was 10% greater than that in the global market [IEA 2023]. In Poland, the renewable energy market is developing very rapidly. As indicated by the Energy 2023 report published by the Polish Central Statistical Office [Statistics Poland 2023a], in 2021, Poland was in 4th place in the European Union in terms of the amount of energy produced from renewable sources.

The problem of meeting the constantly growing energy needs of societies that care for the environment is often considered by researchers not as a separate problem but holistically as part of a larger entity, the food–water–energy nexus [Campana and Lawford 2022]. The main threats to the elements of this system from a global perspective are the growing demand for resources and climate change, which makes it necessary to make efforts for better use of available assets [Cansino-Loeza et al. 2022]. In the European region, the drive to more efficiently use these resources to meet society's needs is compounded by rising prices for both food and energy, resulting from the market recession caused by the Ukraine war [Mbah and Wasum 2022]. One of the aspects that can be improved in this regard is the better use of available land resources for certain forms of development demanded. In this context, one solution of interest to researchers in recent years is agrivoltaics (AV), which involves the dual use of the same land resources: agricultural land and solar photovoltaic farms [Mamun et al. 2022]. One of the advantages of this concept is the coexistence of two utility functions in the same area that are not competitive with each other [Weselek et al. 2019]. As studies have shown, AV systems not only allow better utilisation of available land resources but can also significantly improve the efficiency of agricultural production. Studies have shown that such systems can contribute to stabilizing agricultural production by reducing the volume of production in years with favourable climatic conditions but contribute to reducing losses in drier periods, to which land without irrigation systems is particularly exposed [Amaducci et al. 2018, Weselek et al. 2021]. In addition to the positive impact on agricultural production itself, AV systems can increase the profitability of agricultural activities by generating additional income from energy production [Malu et al. 2017] and (in the case of off-grid systems) lead to greater energy independence in rural areas [Harinarayana and Vasavi 2014].

One of the key issues in the context of the development of AV is the identification of an appropriate location for investment. The quality and usefulness of the results of the evaluation are directly influenced by the criteria (their selection and relevance) and methodology used in the assessment itself. Analysis of the suitability of specific sites for the location of solar farms has been the subject of many studies in recent years [Almasad et al. 2023]. An approach often used in evaluating areas for solar farms has been to use the geographic information system (GIS) environment and various multi-criteria analysis methods, such as analytic hierarchy process (AHP) [Ruiz et al. 2020, Prieto-Amparán et al. 2021], weighted overlay (WO), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), simple additive weighting (SAW) [Shehab et al. 2024] are often used to evaluate the suitability of areas for solar farms. Vrînceanu et al. [2022] used a GIS weighted overlay approach to analyse the Romanian area, taking into account 10 different factors (including orography and climatic and anthropogenic conditions), and the results revealed that nearly 30% of the entire country's land area has relatively high potential for siting photovoltaic (PV) farms. An example of a study on a smaller scale is the work of Yousefi et al. [2018], who used a combination of GIS and Boolean fuzzy logic on the terrain fit of an area of approximately 30,000 km^2 in Iran for PV. The authors, based on an analysis of 9 different criteria, determined matching areas that were mostly near two urban centres.

For AV systems, the selection of criteria is a more complex process than monoculture land development for PV farms. The increase in the level of complexity of the issue, compared with that of ordinary PV systems, is caused by the necessity of considering the evaluation of the agricultural aspect and the criteria directly arising from it. Factors such as climatic conditions, land use, and orography are crucial from the perspective of economic viability and the effective coexistence of PV systems with agricultural land use. The literature analysis, in which selected items from 2018–2023 were collected [Alami Merrouni et al. 2018, Doorga et al. 2019, Colak et al. 2020, Ruiz et al. 2020, Albraheem and Alabdulkarim 2021, Günen 2021, Munkhbat and Choi 2021, Ouchani et al. 2021, Prieto-Amparán et al. 2021, Rios and Duarte 2021, Settou et al. 2021, Sun et al. 2021, Elboshy et al. 2022, Rekik and El Alimi 2023, Raza et al. 2023], revealed that different sets of criteria were used to determine optimal locations for PV systems, among which we can distinguish climatic criteria, orography, and criteria related to land use (fig. 1).

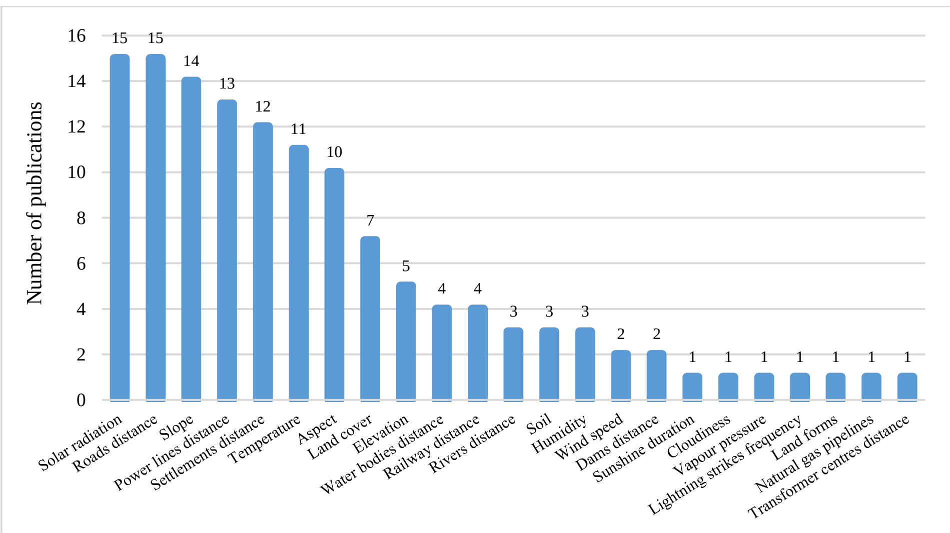

Fig. 1. Criteria used in the selected literature for PV farm location assessment

Although some of the criteria are mentioned in almost every literature item discussed (solar radiation, distance from roads, slope), some criteria are less frequently considered by authors (such as elevation or humidity). In addition to discrepancies in the selection of criteria, the subjectivity of the assessment can be influenced by the choice of weights for individual criteria. In practice, the relevance of individual criteria is commonly determined by the judgement of experts (e.g. from the solar power sector, scientists), and the subjectivity factor can be minimised by formulating final weightings based on a synthesis of judgements from a group of specialists originating from different sectors.

This study attempts to estimate the suitability of the eastern Polish region for AV installations. An additional objective of this work is to supplement existing knowledge on the use of the AHP method in assessing the suitability of areas for AV by evaluating the impact of criteria selection on the results. The dependency of the analysis results on the selection of criteria is obvious in the multi-criteria analysis (MCA) methods. This paper attempts to assess the scale of this dependence in a complex spatial environment when assessing the suitability of an area for a specific type of investment, such as solar farms located on agricultural land. To the best of the authors' knowledge, this issue has not yet been considered in determining optimal AV areas. The structure of this paper is as follows: 2 – characteristics of the research area, 3 – materials and methods, 4 – results, 5 – conclusion and discussion.

STUDY AREA

Lublin Voivodeship is an administrative unit of Poland with an area of 25,122 km^2 (fig. 2) located in the eastern part of the country (36), which is also a separate region in the NUTS-2 classification with evidence code PL31. The capital and largest city of Voivodeship is Lublin. In addition, there are 50 smaller cities, among which the largest in terms of population is Zamość (58,942 citizens), and the smallest is Józefów on the Vistula River (817 citizens) [Statistical Office in Lublin 2023a].

According to the Köppen-Geiger classification [Kottek et al. 2006], the study area is located in a continental climate zone characterised by a lack of a dry season and with a warm summer. The growing season in Lublin Voivodeship (which is a period with an average daily temperature above 5°C) lasts an average of 220–230 days, whereas the average for Poland is 224 days [Tomczyk and Bednorz 2022]. High variability in weather conditions in the Polish region translates into high variability in PV module operating temperatures, which can vary between –20°C and +70°C [Matuszczyk et al. 2015]. The study area is characterised by very good insolation conditions on a country-wide scale. According to the Global Solar Atlas (based on average values for the period 1994–2018), the average annual sum of global horizontal irradiance (GHI) in the Lublin Voivodeship area is 1122 kWh m^{-2}, whereas the average for Poland is 1086 kWh m^{-2}. At the point with the lowest recorded value, radiation amounted to 1086 kWh m^{-2}, which can still be considered suitable solar conditions for the deployment of solar energy systems [Klugmann-Radziemska 2014, Pedrero et al. 2019]. The digital elevation model (DEM) analysis revealed that Lublin Voivodeship is quite differentiated in terms of terrain elevation. The altitude of the land in the study area ranges from 101 to 388 meters above sea level. The relief of the Lublin Voivodeship is quite diverse and consists of the Central Poland Lowlands, Lublin-Lviv Upland, Polesie, Volhyn-Podole Upland, and Northern Subcarpathians [Solon et al. 2018]. There are numerous territories of high natural value within the study area, including 2 national parks (Roztoczański and Poleski), 17 landscape parks, and numerous protected landscape areas and nature reserves.

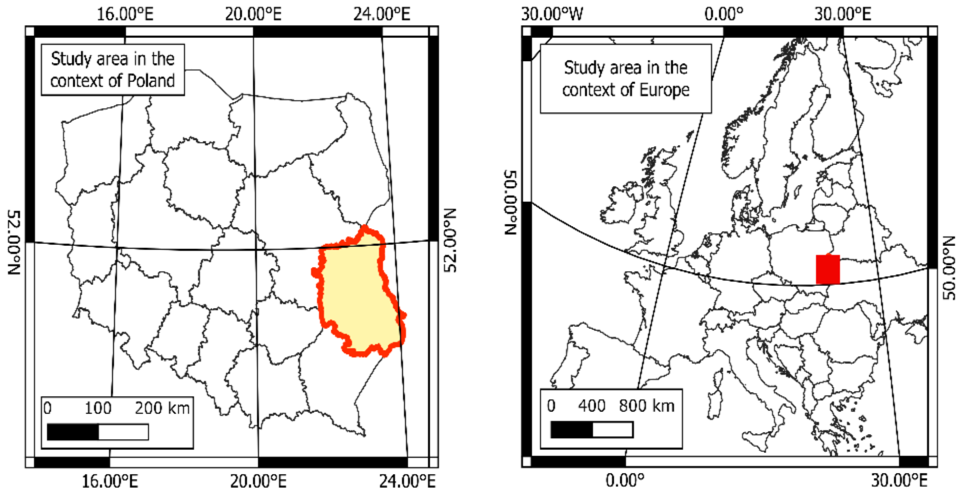

Fig. 2. Study area location in the context of Poland and Europe

At the country level, Lublin Voivodeship is an important hub of plant agricultural production. According to the Polish Central Statistical Office report for 2022 [Statistical Office in Lublin 2023b], Lublin Voivodeship is among the leaders in the country in terms of global agricultural production (crop and livestock), with a share of 8.5% of total domestic production in the analysed period. The report indicates that cereals (28.9%), fruits (25.5%), industrial (14.3%), and vegetables (13.8%) accounted for the largest share of total crop production in 2021. In the overall crop structure of the study area, it is possible to distinguish plants which, based on empirical analyses, show good performance (understood as higher overall land productivity) in AV cultivation: wheat (3,298 km^2 of arable land in 2022), corn (765 km^2) and potatoes (99 km^2) [Trommsdorff et al. 2021, Jo et al. 2022]. Agricultural land makes up the vast majority of the total land cover within the study area. In this work, the following manifestations of agricultural land use are distinguished: arable land, grassland vegetation, and permanent crops such as orchard plantations and plant nurseries. The region's problem is the relatively high fragmentation of agricultural farms. According to the 2020 Agricultural Census, in the year of the survey, almost 37% of all farms had areas of 2–5 ha, and the average area of a single farm was 8.6 ha, which was smaller than the average for Poland (11.4 ha) [Statistics Poland 2023b].

Land with various forms of agricultural use is the main form of land use in the study area, and according to data from the CLC database, it covers an area of 16,939 km^2, accounting for more than 67% of the total area (fig. 3).

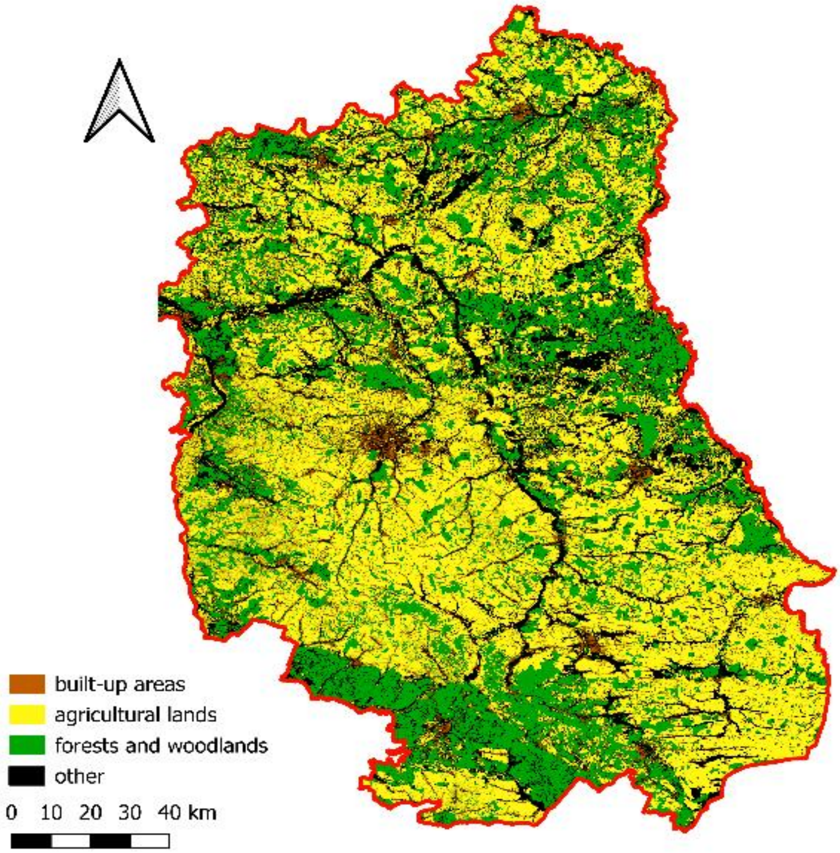

Fig. 3. Forms of land use in Lublin Voivodeship [own elaboration based on CLC data]

The area's agricultural land structure includes 72% non-irrigated arable land, 17% pasture, meadow, and other permanent grasslands used for agriculture, 5% complex cropping patterns, 5% land occupied mainly by agriculture, with significant areas of natural vegetation, and 1% fruit tree and berry plantations.

MATERIAL AND METHODS

According to the adopted methodology, the starting point was to set evaluation and exclusion criteria for the study area (fig. 4). The evaluation criteria were analysed via the AHP method to establish weighting values. In the next stage, the spatial data was collected and processed in QGIS software. The processing resulted in 3 suitability maps of the area for the established alternatives.

This study used spatial and numerical statistical data as research material. The main analytical material was spatial data in the form of digital elaborations. Details of the spatial layers used are shown in table 1.

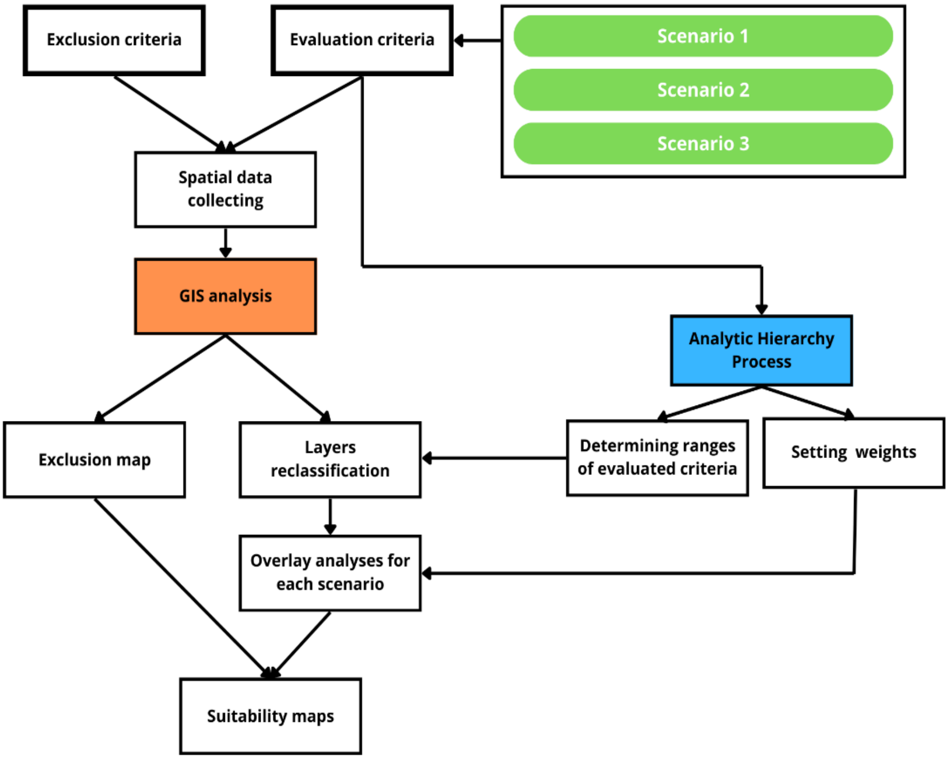

Fig. 4. Flowchart of the work

One of the limitations of the work is not taking into account climatic conditions (insolation, temperature). Although they significantly affect module performance in practice [Zondag 2008, Chikate and Sadawarte 2015], their variability due to the scale of the study adopted is small. Based on Global Solar Atlas data, the variation in annual GHI totals between points in the area is a maximum of 61 kWh m^{-2}, and in 95% of the area, the differences are no more than 40 kWh (1100–1140 kWh). In the case of the average annual temperature, the difference between the lowest and highest values was 1°C, which theoretically could translate into a difference in panel efficiency of around 0.3% [Nájera-Ruiz et al. 2018]. Limitations of the work also include the lack of assessment of the soil quality, the reason for which was the lack of adequate quality spatial data. According to Kurowska et al. [2022], under Polish conditions, the use class of the soil translates directly into the legal conditions of the area. In the case of soils of classes I–III the development of AV can be associated with certain restrictions (planning permission), which makes the legal procedure more complicated and expensive. In addition, the lack of detailed analysis of the different types of crops found in the area in terms of their predispositions can be considered a limitation.

Table 1. Spatial data used in the study

Data	Aim of use	Type/ format	Spatial resolution	Year	Source
Polish database of topographic objects (BDOT10k)	land cover	vector/ shp	–	2023	Polish Central Office of Geodesy and Cartography (https://www.geoportal.gov.pl/)
CLC	land cover	vector/ shp	–	2018	Copernicus Land Monitoring Service (https://doi.org/10.2909/cd534ebf-f553-42f0-9ac1-62c1dc36d32c)
DEM	orography	raster/ tiff	1 arc-second	2014	U.S. Geological Survey (https://earthexplorer.usgs.gov/)
GHI	Solar resources	raster/ tiff	9 arcseconds	1994–2018	Global Solar Atlas (https://globalsolaratlas.info/)

Evaluation criteria

For the analysis of fit, 8 criteria most frequently repeated in the problem literature were extracted (fig. 1). Among these proximity to roads (100%), slope (93%), proximity to power lines (87%), proximity to settlements (80%), temperature (73%), aspect (67%), land use (47%), altitude (33%) and proximity to railway lines (27%). For the selected criteria, 5 ranges of values were determined, which were then assigned to five classes of fit: low, moderately low, medium, moderately high, and high. The designated scores were assigned to fit classes from 1 to 5, with class 1 indicating high suitability of the area, class 5 indicating low suitability, and values 2–4 represented the respective intermediate assessments (tab. 2).

Based on the classes assigned to each range for each criterion, maps of the suitability of each criterion were developed (fig. 5).

The cells were assigned values from a scale of 1–5, after which overlay analysis was carried out on the basis of the values assigned to each cell. The following subsections provide a detailed description of the individual criteria selected as comparison factors and their role in the overall fit analysis.

Table 2. Selected criteria

Criterion type	Criterion	Units	Adopted ranges of values	Values after reclassification
Orography	slope	degrees	15–20	5
			10–15	4
			6–10	3
			3–6	2
			0–3	1
	aspect	degrees	N (330–360/0–30)	5
			NE (30–60), NW (300–330)	4
			E (60–120), W (240–300)	3
			SE (120–150), SW (210–240)	2
			S (150–210), flat	1
	elevation	m	101–196	5
			197–291	3
			292–388	1
Land use	roads distance	km	>3	5
			1.51–3	4
			0.81–1.5	3
			0.31–0.8	2
			0–0.3	1
	transmission lines distance (medium voltage)	km	>3	5
			1.51–3	4
			0.81–1.5	3
			0.31–0.8	2
			0–0.3	1
	cities distance	km	25–50	5
			15–25	4
			10–15	3
			5–10	2
			0–5	1
	land cover	CLC code	242, 243	5
			222	3
			211, 231	1
	railway distance	km	>3	5
			1.51–3	4
			0.81–1.5	3
			0.31–0.8	2
			0–0.3	1

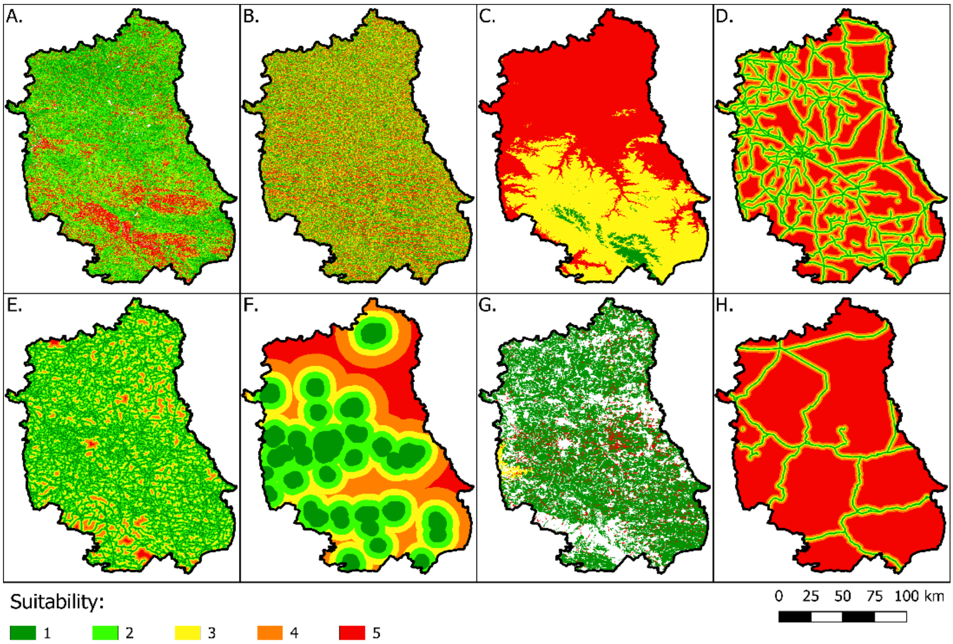

Fig. 5. Study area land suitability according to each criterion: A – slope, B – aspect, C – elevation, D – distance from major roads, E – distance from power lines, F – distance from cities, G – land use (agricultural land only), H – distance from railroads

Orography

The desirable terrain for investment in terms of slope (A) is flat or slightly sloping land. Locating PV farms in such areas allows for significant cost savings, particularly at the construction stage. For the same reason, areas with extremely steep slopes would require high capital expenditures, making them financially unviable. The ranges of values for slope were formulated based on Yang et al. [2019], who recommended 20 degrees as the upper limit of slope for the location of solar farms.

The aspect (B) is a factor that can help or hinder the optimal positioning of panels in relation to direct incident solar radiation. The optimal tilt direction of panels with a constant orientation results from the geometric relationship between the sun and the Earth and, in practice, depends primarily on latitude. In the case of northern latitudes, it is suggested that the panels slope in a southerly direction, so the best direction of sloping land for investment is characterised by land tilted in a southerly direction or flat. In this study, the aspect representation was an azimuth.

An increase in altitude can lead to better insolation (greater atmospheric transparency) [Redi et al. 2010] and decrease in temperature, which can translate into better performance of PV panels [Barbón et al. 2023]. An ambiguous issue is the effect of height on costs at the construction stage. On the one hand, regions with higher altitudes may be less expensive, making them more accessible for potential investors [Barbón et al. 2023]; on the other hand, the cost of bringing the necessary infrastructure and connection to the network may be greater in these regions [Adjiski and Serafimovski 2024]. This study assumes that higher altitudes are better for locating solar installations, and according to this approach, three classes of suitability were adopted.

Land use

Roads proximity (D) translates into better accessibility of the land, which is important at the construction stage and helps reduce investment costs; however, at the operation stage and related inspection as well as maintenance works, transportation accessibility can be economically advantageous. This study assumes that areas more than 3 km from such infrastructure have the lowest rating (5) for suitability.

Proximity to the electrical transmission network (E) at the construction phase translates into lower costs of connecting the installation to the grid, whereas during the operating period, this results in lower energy losses during transmission. In this study, the accessibility of medium-voltage transmission lines was evaluated, and the distance ranges for infrastructure were taken over the same range as those for road infrastructure.

Settlement proximity (F) is an important component of economic viability. The vicinity of groups of electricity consumers leads to lower transmission losses and sometimes also a reduction in costs for the construction and maintenance of the power grid. In the detailed assessment of matching areas, the classification proposed by Raza et al. [2023] was adopted, according to which the best areas for investment are those located no further than 5 km from cities.

Based on the CLC classification, 5 types of agricultural land use forms (G) occurring within the study area were distinguished: non-irrigated arable lands (211 CLC code), fruit trees and berry plantations (222), pastures (231), complex cultivation patterns (242) and lands principally occupied by agriculture, with significant areas of natural vegetation (243), which were then classified into 3 groups of suitability.

The criterion of railway line proximity (H) can facilitate the integration of the installation with the power grid by utilising the existing railway electrical infrastructure, which can translate into reduction of connection costs and lowering of energy transmission losses, improving the overall efficiency of the system. The construction of PV installations in the proximity of railway infrastructure may facilitate integration with the grid by utilising the railway's spare connection capacities, which may translate into lower investment costs and allow for better use of the existing infrastructure [Shen et al. 2020, Binduhewa 2021]. The rating ranges for this criterion were adopted in the same way as those for distance from the road and energy infrastructure.

Exclusion criteria

The following areas were considered unsuitable for AV systems: territories under legal protection (Natura 2000, national and landscape parks, and nature reserves), sites located closer than 300 m from flowing waters (due to the risk of flooding), and urban areas. In addition, areas that were not agricultural land were excluded from the evaluation. Based on the above criteria, excluded zones were designated (fig. 6).

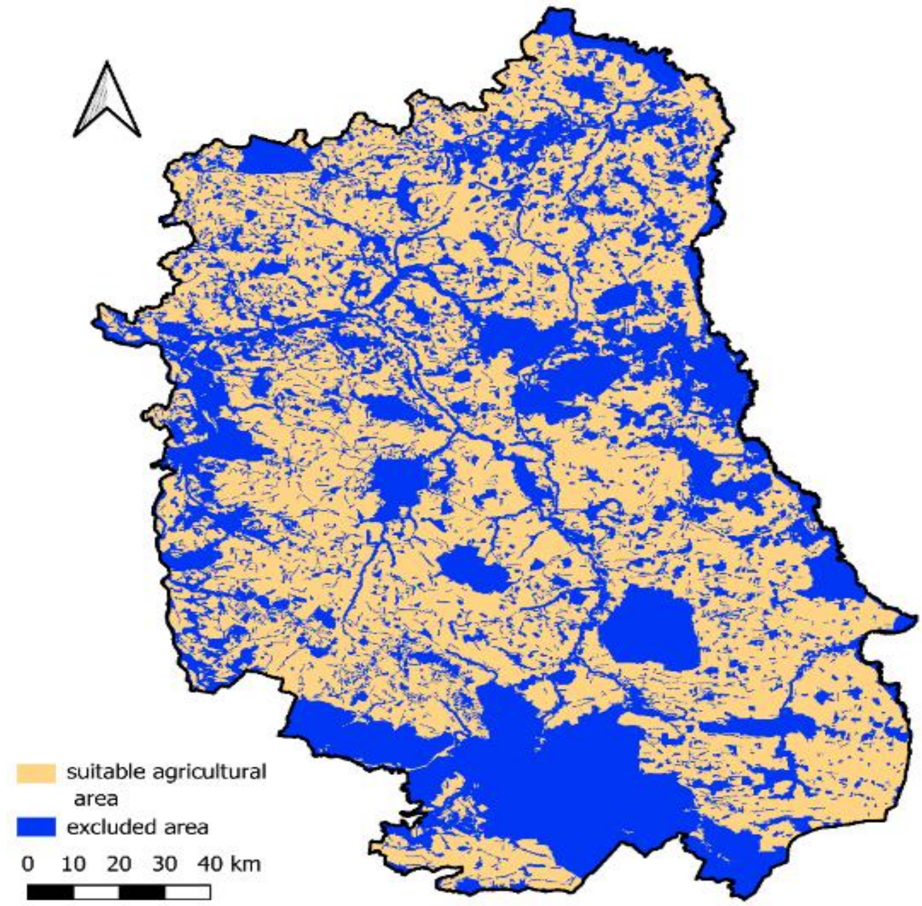

Fig. 6. Excluded areas based on the adopted criteria

Based on adopted criteria, suitable land occupy a total of 14,230 km^2 of the study area. This area also accounted for 84% of all agricultural land and nearly 57% of the Voivodeship area.

Analysis of alternatives

In the analysis of alternatives, results were compared across the group of all criteria in Scenario 1 (S1) to Scenario 2 (S2) including only orography criteria and Scenario 3 (S3) land use. The criteria were evaluated and compared according to the principles of the AHP, which is one of the multi-criteria decision-making (MCDM) methods introduced by T.L. Saaty [Saaty 1987]. The first step was the creation of a preference matrix in which comparison was made between the criteria included in the pairwise analysis with adopted scale 1–9 (tab. 3). The comparative values were determined according to Rios and Duarte [2021].

Table 3. Pairwise comparison of criteria

Factor	A	B	C	D	E	F	G	H
A	1	1/3	9	1/3	1/7	1	1/2	9
B	3	1	9	1	1/4	3	2	9
C	1/9	1/9	1	1/9	1/9	1/9	1/9	1
D	3	1	9	1	1/4	2	1	9
E	7	4	9	4	1	7	5	9
F	1	1/3	9	1/2	1/7	1	1/2	9
G	2	1/2	9	1	1/5	2	1	9
H	1/9	1/9	1	1/9	1/9	1/9	1/9	1
Sum	17.22	7.39	56.00	8.06	2.20	16.22	10.22	56.00

where 1 indicates equal importance of both criteria, and 9 indicates extreme preference for a given criterion over the reference criterion. A characteristic feature of the comparison matrix is the reciprocal relationship between pairs of criteria, which can be expressed as:

$$X_{ij} = \frac{1}{X_{ji}} \tag{1}$$

S1 involved the entire matrix, whereas in S2 and S3 only criteria corresponding to them were taken into account and the weights for every scenario have been determined (tab. 4).

Table 4. Scenarios criteria and weights

Criterion	Scenario 1	Scenario 2	Scenario 3
A	0.08	0.32	0.00
B	0.16	0.63	0.00
C	0.02	0.05	0.00
D	0.14	0.00	0.17
E	0.39	0.00	0.53
F	0.08	0.00	0.11
G	0.12	0.00	0.16
H	0.02	0.00	0.03

To validate results, the consistency of the matrix for each scenario was checked. For this purpose, the Consistency Index was determined according to the equation [Saaty 1987]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where λ_{max} represents the maximum eigenvalue of the matrix and n represents the number of criteria. Based on the values of CI, the Consistency Ratio was calculated as follows:

$$CR = \frac{CI}{RCI} \quad (3)$$

where the values of the Random Consistency Index (RCI) dependent on the number of elements compared in each set were used as the RCI values [Golden and Wang 1989].

Based on the weights determined overlay analyses were carried out in the QGIS software for each scenario. The reclassified evaluation values of each criterion were multiplied by the weighting factors and then summed for the criteria in each set, resulting in three alternative maps of the suitability of the area for AV.

RESULTS

As a result of the exclusion criteria, of the 16,939 km^2 of total agricultural land in agricultural use, 3,630 km^2 were excluded. This approach was applied in an unchanged form for each of the analysed scenarios.

Based on the adopted ranges of values for individual criteria and the weights that were assigned to them, areas predisposed for AV development were determined (fig. 7). For the scenario considering all 8 criteria, the percentage of highly suitable areas is extremely small and the smallest of all 3 scenarios, while the vast majority of land evaluated is classified as moderately highly suitable.

Generally, based on this assessment, the spatial conditions of Lublin Voivodeship create fairly good predispositions for the development of AV, to which both the high availability of agricultural land (and favourable forms of its use), well-developed infrastructure, and orographic conditions contribute. Highly suitable areas accounted for 163.2 km^2 and this corresponds to 1.2% of all suitable agricultural lands. The rest of the agricultural land was classified as follows: moderately high suitable – 9,798.6 km^2, moderately suitable – 4233.6 km^2, and moderately low suitable – 34.2 km^2. In this scenario, areas with a moderately high suitability had the relatively largest share, and the smallest number of areas were found to have a high fit compared with S2 and S3 (fig. 8).

In S2, in which only the orography of the site was evaluated, the results of the analysis were the most balanced compared the other two approaches, and no class of fit could be considered dominant within the study area. The largest share (36%) was held by areas categorised as moderately highly suitable, and slightly fewer (30%) were categorised as medium. This analysis showed the highest share of highly suitable areas, accounting for 13% of the total. The dominant level of suitability in S3 was moderately high (67%), and 10% of the area was classified as highly suitable. No low-fit areas were observed in any of the analysed cases.

The discrepancies in the results for the individual scenarios can be considered both at the level of the raw result layers (fig. 9) and after their reclassification, which involves assigning specific ranges of result values to the corresponding suitability classes. Analysis of the raw data layers revealed that when all criteria were included, the mean value of the derived suitability was the highest in S2 analysis (2.67) and the lowest in S3 analysis

(1.80), which indicates that the conditions of the area assessed in S3 are relatively the most favourable. The spread of values for which the standard deviation was taken as the indicator ranged from 0.41 (all criteria) to 0.97 (orography).

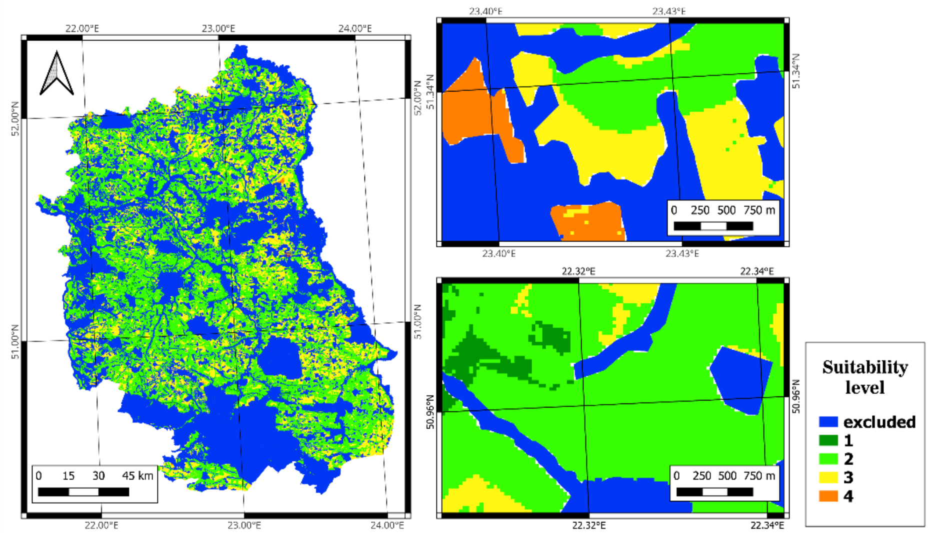

Fig. 7. Suitability of the area based on all criteria evaluation

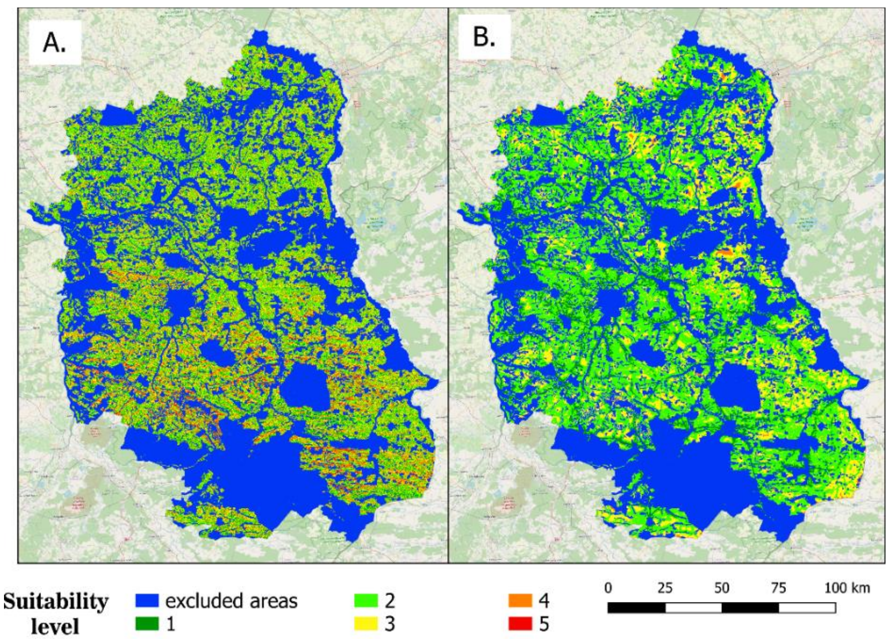

Fig. 8. Comparison of suitability alternatives: A – orography, B – land use

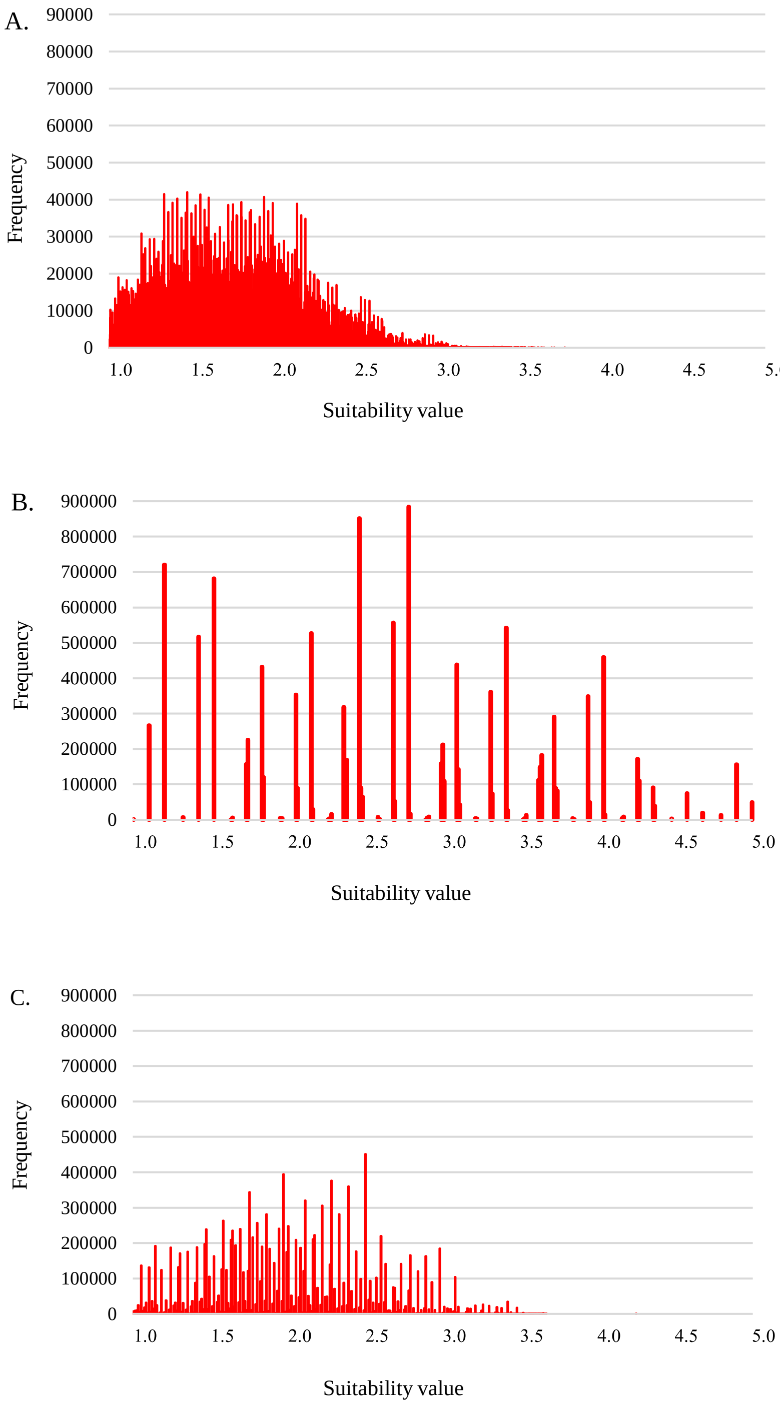

Fig. 9. Histograms of suitability values before reclassification: A – all criteria, B – orography, C – land use

The sensitivity analysis compares the suitability map derived from orography and land use to two alternative criteria selection scenarios: orography only and land use only (Fig. 10).

In both cases, the differences between the maps were at most two classes. More consistency with the S1 analysis was maintained by S3 analysis. In this case, as many as 89% of the sites overlapped, and a difference of one class was observed in 11% of the total area assessed. The analysis of orography differed significantly more from the overall analysis, and agreement between the studies was observed in 71% of the area, whereas the rest of the area showed a difference of one class

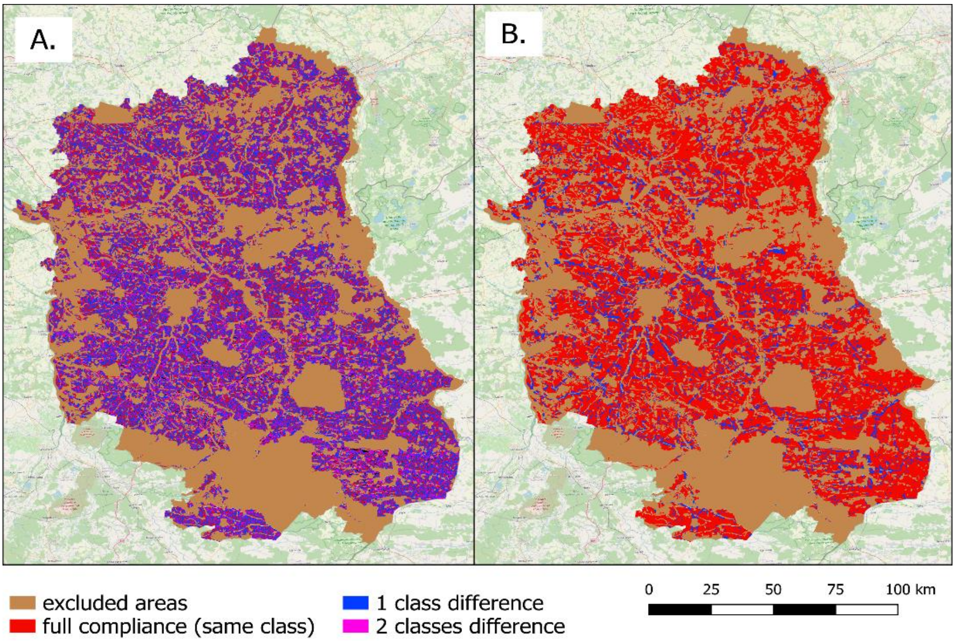

Fig. 10. Comparison of differences between scenarios: A – all criteria vs orography, B – all criteria vs land use

CONCLUSION AND DISCUSSION

This paper addresses the evaluation of the spatial conditions of the Lublin Voivodeship for the development of AV in light of MCDM. Using the GIS environment and AHP method, a comprehensive assessment of the area was carried out in which a total of 8 criteria. In addition to the analysis of the entire set of criteria, two additional analyses were carried out in parallel: the first assessed only orography, and the second assessed land use.

An analysis of the sensitivity of the AHP assessment to the selection of criteria revealed that in a complex spatial environment, the number of factors under evaluation is not always crucial. When comparing the scenario with the full set of criteria evaluated to the two alternatives in which the number of criteria was truncated, a relatively high convergence of results was observed in comparison of S1 and S3. In S2, significantly greater inconsistency was observed, reaching a maximum of 2 classes. For both S1 and S2, the key influence of proximity to the transmission network (the dominant criterion) on the results can be observed. The most suitable areas at 97.4% in S1 and 98.1% in S2 were within 300 m distance of a medium voltage power lines. In the analysis of the orography, land orientation was the dominant criterion, and it can be observed from the analysis that the areas least suitable for AV development (classes 4 and 5) are predominantly located in the southern part of the study area, where the relief is more varied and slopes as well as altitudes are relatively higher.

In addition to the selection of evaluation elements themselves, a problematic issue is the evaluation of their importance to each other, which, in the case of MCA, is always influenced by the subjective point of view of the person making the evaluation. An effective way to reduce uncertainty is to determine the importance of criteria based on consultations with expert groups and to synthesise the resulting assessments in a comparative matrix. The selection of appropriate evaluation factors for the determination of suitable sites for AV as well as PV farms in general is a complex problem and should be carried out based on the purpose of the specific analysis. Future research in this area should focus on developing models and methods for the selection of criteria and their evaluation, which are less sensitive to the subjectivity of evaluation and are more based on universal factors.

Potential directions for future research that could significantly deepen the analysis carried out should also include extending the spatial scale (e.g. to the national level), with consideration of the variability of climatic conditions, including solar radiation in particular. An aspect that requires additional analysis is also the economic viability of the investment, which in the case of AVs would require many additional aspects to be taken into account, including: investment costs (during the construction phase) which are higher than for PV; an assessment of different types of agricultural crops and the impact of partial shading on their yield; as well as local electricity and crop prices. A future extension of the analysis could also include soil conditions and the resulting legal prerequisites that realistically determine AV development opportunities. However, the analysis of the legal conditions may be problematic on Polish grounds, as the very concept of ‘agrivoltaics’ does not exist in the country's legal system and therefore AVs are often treated like typical PV farms, with the same limitations applied to them (e.g. significantly restricted use of soil in class III and better). However, it is important to consider that the lack of a clear definition of this concept leaves a lot of space for subjective interpretation of the law, which generates additional problems in unambiguously assessing the legal potential.

In an assessment taking into account all criteria, over 98% of all suitable areas were classified as “moderately suitable” and “moderately highly suitable”. The percentage of land that could be considered ideal (high suitability) is relatively small, but there is a large base of land that could be used by investors for AV with the appropriate technological and design approach. It can also be expected that sites identified as less suitable for AV may be relatively cheaper to purchase due to relatively poorer infrastructure accessibility, greater distance from cities, or less favourable terrain, which may partially compensate for unfavourable conditions. An important tool in spatial policy that could contribute to improving the profitability of investments on less suitable sites could be the implementation of subsidies and financial support programmes for investment projects. Furthermore, from the perspective of local governments, agrivoltaics can be a form of land use that supports the local economy and contributes to increased energy security. However, the real possibilities for the development of this type of installations would require adjusting spatial policy both at the national level and in local development plans as a new form of agricultural land use.

Notably, the results of this study are related to a specific area with specific spatial conditions. Changing the area of analysis can also significantly affect the final result, in addition to the selection of criteria and the weights assigned to them. The use of GIS tools in cooperation with MCDM to select suitable sites for agribusiness investment has advantages such as virtually unlimited possibilities for selecting assessment aspects and supporting the decision-making process based on the individual preferences of specific users. On the other hand, problematic aspects include the high sensitivity of the analysis to the human factor. The spatial aspect of evaluation can pose additional challenges in making a decision that is as close to optimal as possible, alongside the careful selection of evaluation elements and their mutual relationships. Criteria that are crucial in one area may have a marginal impact on the outcome in another due to small variability.

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DOROTA JAGIEŁŁO

Alternatywne do azotu metody maksymalizacji plonowania roślin uprawnych

Alternative to nitrogen fertilization methods for maximizing crop plants yields

Abstrakt. Azot, jako najważniejszy pierwiastek warunkujący jakość i wielkość plonowania każdej rośliny uprawnej, powinien być dostarczany roślinie w sposób racjonalny, umożliwiając maksymalne wykorzystanie jego zasobów przez roślinę i nie dopuszczając do gromadzenia jego nadmiaru w profilu glebowym. Forma mineralna jest najwygodniejsza technologicznie oraz pozwala precyzyjnie zaplanować i podać odpowiednią dla uprawianego gatunku dawkę tego pierwiastka. Jednak z uwagi na potencjalne przenikanie nadmiaru azotu z nawozów mineralnych do gleby i wód gruntowych w praktyce rolniczej poszukuje się alternatywnych metod prowadzących do zwiększania plonowania. W niniejszej pracy opisano znaczenie azotu w odżywianiu roślin i jego wpływ na glebę. Przedstawiono także alternatywne do mineralnego nawożenia azotem sposoby jego dostarczania (przez stosowanie np. nawożenia naturalnego, organicznego, pochodzenia odpadowego, uprawę roślin przedplonowych wiążących azot z powietrza atmosferycznego) oraz sposoby modyfikacji metabolizmu roślin przez biostymulację preparatami zawierającymi: kwasy humusowe, glony, aminokwasy, a także mikroorganizmy. Ograniczenie gromadzenia się w środowisku przyrodniczym zanieczyszczeń pochodzenia rolniczego jest ważne, ponieważ służy przywróceniu biologicznej równowagi ekosystemów.

Słowa kluczowe: azot, plonowanie, nawożenie, biostymulatory

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WSTĘP

Zadaniem rolnictwa – sektora gospodarki odgrywającego szczególną rolę poprzez zaspokajanie podstawowych potrzeb ludzkości – jest produkcja wysokich, dobrych jakościowo plonów przy ekonomicznie uzasadnionych nakładach i ochronie środowiska przyrodniczego. Właściwy poziom nawożenia mineralnego warunkuje dobry wzrost roślin i wysokie plony, jest jednak czynnikiem niepozostającym bez wpływu na środowisko naturalne [Murawa i Przyborowski 2014]. O tych kwestiach mówi także strategia Europejskiego Zielonego Ładu, która zakłada do 2030 r. zmniejszenie o co najmniej 50% strat składników odżywczych i zmniejszenie o co najmniej 20% zużycia nawozów mineralnych, aby przywrócić zdrową równowagę ekosystemów [Wiśniewski i Marks-Bielska 2022, Stefanis i in. 2024]. Zatem niezwykle istotne jest opracowywanie nowych metod przywracania naturalnych mechanizmów stabilności ekosystemów [Dara 2019, Baker i in. 2020, Hamid i in. 2021].

Główna koncepcja nawożenia azotem służy zwiększaniu wydajności uprawy. Zboża lepiej odżywione azotem przyśpieszają fazy rozwojowe i silniej się krzewią [Faizy i in. 2017], wytwarzają większą biomasę, co pośrednio wpływa na regulację zachwaszczenia [Harasim i Wesołowski 2013]. Podstawowe nawożenie zbóż azotem zwiększa wydajność jednostkową upraw i poprawia jakość pozyskanego ziarna. Uzupełnienie nawożenia dodatkowo siarką wpływa na optymalizację plonowania, ponieważ jej niedobór prowadzi do słabego wykorzystania azotu z nawozów, co skutkuje migrowaniem niepobranego azotu w głąb gleby i do wód gruntowych [Klikocka i in. 2017, Stankowski i in. 2019]. Także Rachoń i in. [2013] potwierdzają wpływ intensywności technologii produkcji polegającej na zastosowaniu większych dawek azotu, na zwiększenie zawartości białka w ziarnie pszenicy zwyczajnej, twardej, orkiszu i jednoziarnistej.

Chęć ograniczenia nadmiernego stosowania nawozów mineralnych, a zarazem uzyskanie wysokich oraz dobrych jakościowo plonów wiąże się również z dostosowaniem dawki azotu w okresie wegetacji do potrzeb pokarmowych i faz rozwojowych roślin [Skudra i Ruza 2016]. W celu uzupełnienia zawartości azotu w glebie nie tylko stosuje się nawozy mineralne, lecz także naturalne, organiczne, biostymulatory mikrobiologiczne i pochodzenia naturalnego [Soppelsa i in. 2019], produkty odpadowe z przemysłu [Klapec i Cholewa 2012] oraz dokonuje się wyboru odpowiedniego płodozmianu [Łagocka i in. 2016]. Należy zaznaczyć, iż nadmierne stężenie azotynów i azotanów w glebie, wodzie czy roślinach będące skutkiem nadmiernego nawożenia mineralnego może stanowić zagrożenie dla zdrowia organizmów żywych. Według Światowej Organizacji Zdrowia (WHO) dopuszczalna norma stężenia azotanów w wodzie przeznaczonej do spożycia wynosi 50 $mg \cdot dm^{-3}$, a azotynów 0,5 $mg \cdot dm^{-3}$ [Rozporządzenie Ministra Zdrowia z dnia 7 grudnia 2017 r.]. Dlatego też celem niniejszej pracy jest omówienie, na podstawie dostępnej literatury, alternatywnych do mineralnego nawożenia azotem upraw rolniczych sposobów prowadzących do zwiększenia plonowania i poprawy jego jakości.

NAWOŻENIE AZOTEM W ODŻYWIANIU ROŚLIN I WPŁYW NA GLEBĘ

Bardzo ważnym składnikiem pokarmowym w produkcji roślinnej jest azot, który w największym stopniu decyduje o wielkości oraz jakości zebranego plonu [Murawa i Przyborowski 2014, Patyra i in. 2022]. Zwiększenie dawki azotu w uprawie pszenicy z 150 kg·ha^{-1} do 200 kg·ha^{-1} skutkowało zwiększeniem wartości wskaźników: kąta nachylenia liści (MTA), indeksu powierzchni liści (LAI), zieloności liścia (SPAD), a także innych badanych parametrów jakościowych oraz zwiększeniem wielkości plonu [Buczek i Jańczak-Pieniążek 2021]. Azot jest także głównym składnikiem chlorofilu i bierze pośredni udział w procesach fotosyntezy [Cetner i in. 2016], syntezie enzymów, fitohormonów i aminokwasów będących składnikiem budulcowym białek strukturalnych [Kubiak-Siwińska i Kotlarz 2023]. Jest również składnikiem biologicznie ważnych związków, tj. kwasów nukleinowych, hormonów roślinnych, metabolitów wtórnych oraz ATP, czyli nośników energii [Podleśna 2018]. Zatem niedobór azotu stanowi czynnik silnie ograniczający wzrost i rozwój roślin. Bogaty rezerwuar azotu cząsteczkowego (78%) stanowi atmosfera ziemska, nie może być on jednak bezpośrednio asymilowany przez rośliny. Redukcję do form łatwo przyswajalnych utrudnia występujące potrójne wiązanie kowalencyjne pomiędzy atomami azotu [Oldroyd i Dixon 2014]. Z nawożeniem mineralnym jest wprowadzany do gleby azot w formie amonowej NH_{4+}, azotanowej NO_{3-} i amidowej $C\text{-}NH_2$ (mocznikowej). Forma azotanowa jest stosunkowo łatwo przyswajalna dla roślin, natomiast jej intensywne pobieranie przez rośliny może przyczynić się do pogorszenia jakości oraz nadmiernej akumulacji azotu w plonie. Łatwo także przedostaje się w głąb profilu glebowego, do wód gruntowych, a także w procesie przemian denitryfikacyjnych ulatnia się do atmosfery, ponieważ nie jest wiązana przez kompleks sorpcyjny gleby [Hołubowicz-Kliza i in. 2021]. Forma amonowa azotu natomiast jest wiązana w glebie, przez co dostępność dla roślin jest dłuższa, jednak przez procesy nitryfikacji zachodzące w glebie przekształca się w lotną formę azotanową [Rutkowska 2020]. Forma amidowa powoduje kilkukrotnie mniejsze zasolenie niż pozostałe, podlega przemianie w glebie do formy amonowej, a w konsekwencji do azotanowej. Stratom azotu można zapobiec, stosując podzielone dawki nawozu, aby roślina w pełni mogła go wykorzystać i by nie dostał się do środowiska naturalnego [Głodowska i Gałązka 2018].

Stosowanie nawozów powinno wpływać na poprawę jakości i żyzności gleby, a także na zwiększenie aktywności drobnoustrojów. Jednak zbyt duże dawki nawozów przyczyniają się do nagromadzenia azotu i amoniaku (forma amonowa azotu), który toksycznie wpływa na rośliny i ogranicza rozwój pewnych grup drobnoustrojów oraz przyspiesza proces nitryfikacji, zakwaszając glebę [Hołubowicz-Kliza i in. 2021]. Stosowanie małych dawek nawozów może powodować natomiast wzrost konkurencyjności pomiędzy roślinami i mikroorganizmami, a w konsekwencji – obniżenie plonu [Galus-Barchan i Chmiel 2019]. Alternatywą może być stosowanie innych źródeł azotu, opisanych poniżej (tab. 1).

Tabela 1. Wpływ alternatywnych sposobów dostarczania azotu na roślinę uprawną i glebę
Table 1. The impact of alternative nitrogen delivery methods on the cultivated plant and soil

Alternatywny do mineralnego sposób dostarczania azotu Alternative methods of nitrogen delivery	Wpływ/Impact	
	na roślinę on the plant	na glebę on the soil
Nawożenie naturalne (np. Biovita obornik, naturalny granulowany obornik zwierzęcy Oboplus, kompostowany obornik dżdżownicowy Agrecol, obornik granulowany bydlęcy, Petro 330 ST BIO, Biopon obornik koński, obornik koński granulowany Florovit Pro Natura) Natural fertilization (e.g. Biovita manure, granular natural animal manure Oboplus, composted vermicompost Agrecol, granulated cattle manure, Petro 330 ST BIO, Biopon horse manure, granular horse manure Florovit Pro Natura)	– źródło niezbędnych składników odżywczych/ source of essential nutrients – wyższe plonowanie przez szybszą mineralizację/ increased yield due to faster mineralization – pozytywny wpływ na bezpieczeństwo wytworzonych surowców do produkcji żywności, tj. zbóż, warzyw, owoców oraz pasz/ positive impact on the safety of raw materials produced for food production, such as cereals, vegetables, fruits, and feedstuffs	– dogodne warunki dla rozwoju mikroorganizmów glebowych/ favorable conditions for the development of soil microorganisms – wzrost poziomu próchnicy/ increase in humus content – przyspieszenie mineralizacji/ acceleration of mineralization – poprawa właściwości biologicznych, fizycznych i chemicznych/ improvement of biological, physical, and chemical properties – poprawa stanu środowiska naturalnego/ enhancement of the natural environment – źródło węgla/ source of carbon
Nawożenie organiczne (np. Bioilsa, ASL, Bio Plantella, Florovit kompost granulowany, kompost ogrodniczy, mączki i wyciągi roślinne) Organic fertilization (e.g. Bioilsa, ASL, Bio Plantella, Florovit granulated compost, horticultural compost, plant-based meals and extracts)	– zmniejszenie zawartości azotanów i azotynów, metali ciężkich/ reduction of nitrate and nitrite concentrations, heavy metal – poprawa cech morfometrycznych/ improvement of morphometric characteristics – zwiększenie plonowania/ increasing in crop yield	– zwiększenie żyzności gleby/ increasing in soil fertility – poprawa retencji wodnej i składników odżywczych/ improvement of water retention and nutrient availability – stymulacja aktywności mikroorganizmów glebowych/ stimulation of soil microbial activity
Nawożenie odpadowe (np. Fertilan, Salmix-1, nawozy struwitowe z osadów ściekowych, nawozy pofermentacyjne z biogazowni) Waste-derived fertilization (e.g. Fertilan, Salmix-1, struvite fertilizers from sewage sludge, post-fermentation fertilizers from biogas plants)	– zwiększanie dostępności azotu/ increasing nitrogen availability	– cenne źródło materii organicznej/ a valuable source of organic matter – poprawa właściwości/ improvement of properties

Alternatywny do mineralnego sposób dostarczania azotu Alternative methods of nitrogen delivery	Wpływ/Impact	
	na roślinę on the plant	na glebę on the soil
Uprawa roślin bobowatych wiążących azot (np. koniczyny, lucerny, łubiny, bobik, groch, wyka) Cultivation of leguminous plants that fix nitrogen (e.g. clovers, lucernes, lupins, faba bean, pea, vetch)	– źródło azotu dla rośliny następczej (tj. mineralizacja przyoranych resztek pożniwnych)/ source of nitrogen for the subsequent crop (i.e. mineralization of incorporated post–harvest residues) – cenne źródło azotu dzięki wsiewkom/ valuable source of nitrogen through cover crops – poprawa wydajności rośliny następczej/ enhancement of subsequent crop yield	– wzbogacenie w przyswajalny azot/ enrichment of available nitrogen – zwiększanie zawartości składników mineralnych/ increase in mineral nutrient content – udział w tworzeniu próchnicy/ contribution to humus formation

Źródło: opracowanie własne na podstawie:/ Source: prepared on the basis of:
https://pnos.pl/, https://zielonepogotowie.pl/, https://grupaazoty.com/, https://target.com.pl/, https://eco-vita.pl/, https://ogrodnik24.pl/, Pilarska i in. 2014, Rogers i Oldroyd 2014, Oleńska 2015, Gawdzik i in. 2015, Pilarska i in. 2016, Łagocka i in. 2016, Kapusta 2017, Cieciura-Olczyk i Prośba-Białczyk 2018, Cieciura-Olczyk 2019, Łabętowicz i in. 2019, Olejnik 2020, Oleś 2021, Patyra i in. 2022, Jama-Rodzeńska i Gałka 2022, Tyburski i in. 2023

ALTERNATYWNE DO MINERALNEGO NAWOŻENIA AZOTEM SPOSOBY DOSTARCZANIA AZOTU

Nawożenie naturalne

Centrum Doradztwa Rolniczego (CDR) zwraca uwagę na ograniczanie stosowania nawozów mineralnych w uprawach i wprowadzenie produkcji zwierzęcej jako nieodłącznej części gospodarstwa, by pozyskiwać własny nawóz naturalny [Sazońska 2020]. Do nawozów naturalnych zalicza się: obornik, gnojówkę, gnojowicę, także odchody, z wyjątkiem odchodów pszczół, guano z przeznaczeniem do rolniczego wykorzystania [Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 24 stycznia 2024 r.]. Wiąże się to z poprawą właściwości biologicznych, fizycznych i chemicznych gleby oraz wpływa bezpośrednio na stan środowiska naturalnego, bezpieczeństwo produkcji żywności pochodzenia roślinnego, tj. zbóż, warzyw, owoców oraz pasz [Patyra i in. 2022]. Rolnicy prowadzący chów zwierząt mają możliwość stosowania nawozów naturalnych bogatych w azot (tab. 2). Jednak stosowanie obornika i gnojowicy wymaga ich uzdatniania. Do metod neutralizacji nawozów naturalnych najbardziej ekologicznych oraz ekonomicznie uzasadnionych należy fermentacja beztlenowa i kompostowanie [Pilarska i in. 2014].

W uprawie ziemniaka, który tradycyjnie był uprawiany po oborniku, ze względu na niedobory tego rodzaju nawozu można zastosować pomiot kurzy. Korzystnie wpływa on na plonowanie ziemniaka oraz innych gatunków roślin, gdyż cechuje się m.in. szybszą mineralizacją substancji organicznej [Cieciura-Olczyk i Prośba-Białczyk 2018]. Pomiot kurzy skutkował także bezpośrednio osiągnięciem największej masy bulw z pojedynczej rośliny ziemniaka odmiany jadalnej, natomiast odmiana skrobiowa osiągnęła najwyższy plon po nawożeniu obornikiem [Cieciura-Olczyk 2019].

Tabela 2. Średnia zawartość azotu w oborniku, gnojówce i gnojowicy w zależności od grupy technologicznej oraz systemu utrzymania zwierząt gospodarskich
Table 2. Average nitrogen content in manure, liquid manure and slurry depending on livestock management group and housing system

Nawóz naturalny Natural fertilizer	System utrzymania Housing system	Grupa technologiczna		
		bydło (powyżej 1 roku) cattle (over 1 year)	trzoda chlewna (powyżej 1 roku) swine (over 1 year)	drób (powyżej 20 tyg. kury, brojlery kurze, kaczki, gęsi) poultry (over 20 weeks: laying hens, broilers chickens, ducks, geese)
Obornik Manure (kg N·t^{-1})	głęboka ściółka deep litter	2,5–3,7	2,7–4	20,7–24,7
	ściołowo bedded	2,3–3,3	1,4–4,3	brak danych/ no data
Gnojówka Liquid manure (kg N·m^{-3})	ściołowo bedded	2,1–3,8	0,7–4,6	brak danych/ no data
Gnojowica Slurry (kg N·m^{-3})	bezściołowo non-bedded	2,9–4,5	2,9–4,3	–
Pomiot ptasi Poultry litter (kg N·t^{-1})	bezściołowo non-bedded	–	–	17,0–32,7

Źródło: opracowanie własne na podstawie Żaba 2024/ Source: prepared on the basis of Żaba 2024

Nawożenie organiczne

Do nawozów organicznych zaliczane są preparaty wyprodukowane z substancji organicznej lub z mieszanin substancji organicznych, w tym komposty, jak również komposty wyprodukowane z wykorzystaniem dżdżownic [Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 24 stycznia 2024 r.]. Ocena bezpieczeństwa nawozów organicznych jest dokonywana wraz z procesem rejestracyjnym w ramach badań urzędowych [Rozporządzenie Komisji (UE) nr 142/2011 z dnia 25 lutego 2011 r.]. Monitorowanie bezpieczeństwa bakteryjnego nawozów organicznych pozwala na ograniczenie dostania się substancji niepożądanych do środowiska, powodujących zanieczyszczenie wód, ekotoksyczne oddziaływanie na organizmy glebowe oraz przenikanie do łańcucha pokarmowego [Patyra i in. 2022].

Żywność pochodząca z gospodarstw nawożonych organicznie charakteryzuje się znacznie niższą zawartością azotanów i azotynów, co zmniejsza nawet o 50% ryzyko dostania się tych związków do organizmu. Przy stosowaniu nawozów organicznych istotna jest niska zawartość metali ciężkich, przede wszystkim kadmu w ziarnie zbóż i w bulwach ziemniaków, natomiast ich podwyższona ilość może być spowodowana przez stosowanie niektórych nawozów mineralnych. Azotany co prawda nie są szkodliwe dla człowieka, jednak łatwo ulegają redukcji do azotynów, które z kolei upośledzają transport tlenu przez krew do komórek w organizmie człowieka [Łagocka i in. 2016].

Zastosowanie nawożenia w postaci nawozu organicznego Bioilsa (o zawartości 12,5% N) oraz nawozu ASL (o zawartości 8%N i 9%S) wpłynęło istotnie na poprawę cech morfometrycznych pszenicy ozimej i zwiększenie plonu odpowiednio o 4,95 $t \cdot ha^{-1}$; 5,32 $t \cdot ha^{-1}$ w stosunku do obiektu bez nawożenia (3,58 $t \cdot ha^{-1}$) [Tyburski i in. 2023].

Nawozy pochodzenia odpadowego

Jako nawozy organiczne mogą być także wykorzystane roślinne pozostałości poprodukcyjne, poprawiające strukturę gleby [Rozporządzenie Ministra Rolnictwa i Rozwoju Wsi z dnia 9 sierpnia 2024 r.]. Wyróżnia się odpady pochodzenia: rolniczego (biodegradowalne z dużych ferm oraz pieczarkarni, biogazowni), komunalne (biodegradowalne osady ściekowe, biomasa odpadowa z terenów zielonych), przemysłowe (głównie popioły z przemysłu cukrowniczego, browarniczego, gorzelniczego, owocowo-warzywnego, mięsnego). Odpady przemysłowe i komunalne po przekompostowaniu znajdują zastosowanie głównie do poprawy właściwości gleb uprawnych. Użycie masy pofermentacyjnej z biogazowni w celach nawozowych przyczynia się do zwiększania dostępności azotu dla rośliny uprawnej (forma amonowa N-NH_4), zawężając stosunek C : N w masie pofermentacyjnej przez degradację materii organicznej. Poferment jest zróżnicowany pod względem jakościowym w zależności od przyjętej technologii produkcji biogazu, zależy także od rodzaju odpadu rolniczego użytego jako wsad (tab. 3) [Łabętowicz i in. 2019]. W osadach ściekowych fosfor i azot stanowią dwa główne pierwiastki, dlatego uzasadniony jest odzysk osadu ściekowego i ponowne wprowadzenie do rolnictwa, przy jednoczesnym kontrolowaniu stężeń metali ciężkich [Gawdzik i in. 2015]. Odpady powinny być przekształcone w gotowy produkt i wrócić do środowiska w postaci nawozów, co jest zgodne z ideą zrównoważonego rozwoju [Geissler i in. 2018]. Dlatego należy zwiększyć działania związane z rozwojem sektora nawozowego mające na celu produkcję nawozów z surowców wtórnych (koncepcja gospodarki o obiegu zamkniętym), w tym z osadów ściekowych [Jama-Rodzeńska i in. 2021]. Jama-Rodzeńska i Gałka [2022] zalecają stosowanie nawozów struwitowych pochodzących z osadów ściekowych (o niższej o ok. 5% zawartości azotu i potasu niż typowe nawozy) łącznie z nawozami mineralnymi.

Tabela 3. Zawartość azotu w wybranych nawozach pochodzenia pofermentacyjnego ($g \cdot dm^{-3}$)
Table 3. Nitrogen content in selected digestate-based fertilizers ($g \cdot dm^{-3}$)

Baza/Base	Dodatek/Additive	NH_4-N
Gnojowica świńska Pig slurry	roślinny/ plant-derived	2,6–2,9
	zwierzęcy/ animal-derived	2,2–3,5
Gnojowica bydlęca Cattle slurry	gliceryna/ glycerol	0,4–1,0
	gnojówka bydlęca, kiszonka owsa, kukurydzy cattle manure effluent, oat and maize silage	2,4

Źródło: opracowanie własne na podstawie/ Source: prepared on the basis of Alburquerque i in. 2012

Pilarska i in. [2016] zaznaczają, iż nawożenie z zastosowaniem pulpy z gnojowicy i buraka cukrowego zasadniczo zwiększyło plon tymotki łąkowej z 12 do 20 g s.m. na wazon. Natomiast zastosowanie pofermentu z gliceryną oraz z wywarem gorzelnianym w obu przypadkach spowodowało zmniejszenie plonu, odpowiednio z 12 i 9 do ok. 5 g s.m. na wazon.

Uprawa roślin przedplonowych wiążących azot

Stosowanie roślin bobowatych w strukturze zasiewów wzbogaca glebę w przyswajalny azot, co jest skutkiem prowadzonego przez nie procesu symbiotycznego z bakteriami *Rhizobium* i *Bradyrhizobium*. Ten proces odgrywa kluczową rolę w obiegu azotu w przyrodzie, jest pożądany w funkcjonowaniu ekosystemów lądowych oraz gospodarki rolnej [Rogers i Oldroyd 2014, Oleńska 2015]. Ilość azotu dostarczanego przez rośliny bobowate waha się od 20 do 200 $kg \cdot ha^{-1}$, uzależniona jest od gatunku, odmiany, wielkości plonu i pH gleby. Ich uprawa ma zatem podstawowe znaczenie ekologiczne dla środowiska naturalnego, a także ekonomiczne, przez obniżenie kosztów nawożenia mineralnego (tab. 4) [Kapusta 2017]. Znaczne ilości azotu niewykorzystane przez same rośliny bobowate, są udostępniane uprawom następczym w postaci przyoranych resztek pożniwnych, które ulegają mineralizacji [Olejnik 2020]. Stosowanie wsiewek z roślin bobowatych stanowi także cenne źródło azotu dla innych roślin w uprawie mieszanej [Oleś 2021]. Duże ilości łatwo przyswajalnego azotu w glebie pozostawia po zbiorze także ziemniak uprawiany po nawożeniu obornikiem, wpływając na poprawę wydajności pszenicy ozimej [Tyburski i in. 2023].

Tabela 4. Ilość azotu wniesionego wraz z resztkami pożniwnymi i nawozami zielonymi z roślin bobowatych ($kg \cdot ha^{-1}$)
Table 4. Amount of nitrogen introduced through crop residues and green manure from leguminous plants ($kg \cdot ha^{-1}$)

Roślina Plant	Zielony nawóz Green manure	Resztki pożniwne Post-harvest residues
Koniczyna czerwona/ Red clover	80–120	80–100
Koniczyna biała/ White clover	60–100	100
Lucerna/ Lucerne	brak danych/ no data	110–185
Łubin/ Lupin	50–100	65–95
Bobik/ Faba bean	80–140	60–80
Groch i wyka/ Pea and vetch	50–80	40–60

Źródło: opracowanie własne na podstawie Krysztoforski 2022/ Source: prepared on the basis of Krysztoforski 2022

MODYFIKACJA METABOLIZMU ROŚLIN POPRZEZ STOSOWANIE BIOSTYMULATORÓW

W produkcji rolniczej obok nawozów i środków ochrony roślin, stosowane są także preparaty stymulujące wzrost i rozwój roślin (tab. 5). Biostymulatory mają cechy, które odróżniają je od innych preparatów ochrony roślin i stymulatorów, tj. substancja lub mieszanina substancji pochodzenia naturalnego lub z dodatkiem mikroorganizmów poprawia stan upraw bez ich niekorzystnego wpływu na środowisko glebowe [du Jardin 2015, Hamid i in. 2021]. Preparaty te zwiększają efektywność wykorzystania składników pokarmowych przez rośliny [Rozporządzenie Parlamentu Europejskiego i Rady (UE) 2019/1009]. Ze względu na brak szkodliwego działania biostymulatorów dolistnych na ekosystem oraz zdrowie człowieka są one coraz częściej stosowane w uprawach [Kocira i in. 2018].

Tabela 5. Wpływ stosowania wybranych preparatów z dodatkiem kwasów humusowych, aminokwasów, alg morskich i żywych mikroorganizmów na roślinę uprawną i glebę
Table 5. The effect of selected preparations containing humic acids, amino acids, extracts from marine algae and live microorganisms on crop plants and soi

Preparaty z dodatkiem Preparation with an additive	Wpływ/Impact	
	na roślinę/ on the plant	na glebę/ on the soil
Kwasów humusowych (np. Elvita Humus, Naturvital-Plus, Rosahumus, Humistar, Humusar, Nanogro Aqua Agrarius) Humic acids (e.g. Elvita Humus, Naturvital-Plus, Rosahumus, Humistar, Humusar, Nanogro Aqua Agrarius)	– zwiększanie intensywności pobierania składników pokarmowych przez korzenie i stymulacja ich rozwoju/ increasing the intensity of nutrient uptake by roots and promoting their development – pozytywny wpływ na procesy zachodzące w komórkach/ positive influence on cellular processes – zwiększanie plonowania i poprawa cech jakościowych plonu/ increase in yield and improvement of qualitative traits of the harvest	– akumulator mikrobiologiczny przyśpieszający rozwój mikroflory glebowej/ microbiological reservoir accelerating soil microflora development – zwiększanie dostępności mikroelementów zawartych w podłożu/ increasing the availability of micronutrients present in the substrate – wzmacnianie struktury i żyzności gleby/ strengthening of soil structural stability and enhancement of soil fertility
Aminokwasów (np. Elvita Amino, AminoVital Power, Amminostim BIO, Shift BIOLCHIM, Protaminal, AGRO-SORB L-Amino + Mg) Amino acids (e.g. Elvita Amino, AminoVital Power, Amminostim BIO, Shift BIOLCHIM, Protaminal, AGRO-SORB L-Amino + Mg)	– wzrost efektywności pobierania i wykorzystywania składników pokarmowych (głównie azotu)/ increasing the efficiency of nutrient uptake and use (mainly nitrogen – utrzymywanie korzystnego pH w komórce roślinnej/ regulation of intracellular pH homeostasis in plant cells – zwiększanie tempa biosyntezy chlorofilu i poprawa efektywności fotosyntezy/ enhancement of chlorophyll biosynthesis rate and photosynthetic efficiency – poprawa plonowania/ improves yield –wspomaganie odporności na patogeny/ supports resistance to pathogens	– brak danych/ no data

Preparaty z dodatkiem Preparation with an additive	Wpływ/Impact	
	na roślinę/ on the plant	na glebę/ on the soil
Ekstraktu z alg morskich (np. Elvita Alga, Vigor55 Lamina, Lamina Power 20, Maral, ALGEX, Algasoil) Extract from marine algae (e.g. Elvita Alga, Vigor55 Lamina, Lamina Power 20, Maral, ALGEX, Algasoil)	– zapobieganie skutkom stresów abiotycznych np. przymrozki, susza, zasolenie/ mitigation of the adverse effects of abiotic stresses e.g. frost, drought, salinity – stymulacja wielkości i jakości plonowania/ stimulation of yield volume and quality – zwiększanie zawartości chlorofilu/ increase in chlorophyll content – działanie regenerujące/ regenerating effect	– korzystne oddziaływanie na mikroorganizmy glebowe/ beneficial effects on soil microorganisms – stymuluja pobierania składników odżywczych/ stimulate the uptake of nutrients
Żywych mikroorganizmów (np. Rhizosum N Plus, Messor Ceres Biotics, Elbio BakFos, Elbio FeN, Elbio Fungibactis, Messor Ceres Biotics) Live microorganisms (e.g. Rhizosum N Plus, Messor Ceres Biotics, Elbio BakFos, Elbio FeN, Elbio Fungibactis, Messor Ceres Biotics)	– stymulacja wielkości i jakości plonowania/ stimulation of yield volume and quality – pobudzanie wzrostu systemu korzeniowego/ stimulation of root system development – poprawa pobierania i akumulacji składników pokarmowych (azot atmosferyczny) oraz związków mineralnych/ enhancement of the uptake and accumulation of nutrients (atmospheric nitrogen) and mineral compounds – ochrona przed patogenami/ protection against pathogens	– poprawa zasobności i żyzności/ enhancement of soil fertility and resource availability – zwiększanie zawartości i dostępności rozpuszczalnych form P, K i Fe/ increased levels of soluble forms of P, K and Fe

Źródło: opracowanie własne na podstawie:/ Source: prepared on the basis of:
https://agrosimex.pl/, https://zielonepogotowie.pl/, https://gumisil.store.pl/, https://farmino.pl/, https://wpolu.pl/, https://chemirol.com.pl/, Informacja końcowa z realizacji projektu… 2015, Arioli i in. 2015, Souri 2016, Shams i in. 2016, Rombel-Bryzek i Pisarek 2017, Chiaiese i in. 2018, Radkowski i in. 2018, Soppelsa i in. 2019, Grzyb i in. 2019, Soppelsa i in. 2019, Szparaga i in. 2019, Khan i in. 2019, Wang i in. 2019, Drobek i in. 2019, Kocira i in. 2020, Pačuta i in. 2021, Gawroński 2021, Janas 2023

Sposób wnikania składników pokarmowych do tkanek rośliny, skład i termin stosowania biostymulatorów powinien być ciągle udoskonalany [Alshaal i El-Ramady 2017], ważna jest także retencja oprysku na liściu (dzięki substancji żelującej), co w konsekwencji daje większą kumulację makro- i mikroelementów w biomasie [Jaskulski i in. 2023]. Biostymulatory można także stosować doglebowo, tj. poprzez roztwory wprowadzane do gleby głównie z substancjami próchnicznymi. Preparaty te mogą być także aplikowane do systemu nawadniającego czy też bezpośrednio do gleby [Drobek i in. 2019], jak również przez podlewanie [Cristiano i in. 2018]. Preparaty dolistne wzbogacane są w różne substancje np. pobudzające metabolizm, zwiększające odporność na choroby czy szkodniki [Knapik 2018]. Należą do nich: ekstrakty z alg morskich [Chiaiese i in. 2018], kwasy humusowe, wyciągi roślinne [Soppelsa i in. 2019, Drobek i in. 2019], aminokwasy i hydrolizaty białkowe [Souri 2016]. Technologia dolistnej biostymulacji jest ciągle udoskonalana, modyfikowany jest skład preparatów. Biostymulatory regulujące wzrost i rozwój roślin mogą zawierać makro- i mikroelementy o zróżnicowanych proporcjach, będące składnikami tych biostymulatorów [Matysiak i Miziniak 2019, Stanisławska-Glubiak i in. 2020].

Biostymulatory zawierające kwasy humusowe

Zastosowanie w preparatach nawozowych kwasów humusowych, których składnikami są kwasy huminowe i fulwowe, pozytywnie oddziałuje na rośliny, powodując zwiększenie intensywności pobierania składników pokarmowych przez korzenie, a także umożliwia dostęp do mikroelementów zawartych w podłożu [Yakhin i in. 2017]. Substancje humusowe wpływają zarówno pośrednio, jak i bezpośrednio na roślinę, w zależności od dawki i stężenia substancji. Jednak mechanizm działania kwasów humusowych na stymulację wzrostu roślin nie jest jeszcze do końca znany [Knapik 2018]. Wielu badaczy wskazuje na szerokie pozytywne odziaływanie kwasów humusowych na glebę i rosnące w niej rośliny [Rombel-Bryzek i Pisarek 2017, Drobek i in. 2019, Soppelsa i in. 2019]. Działają one jak akumulator mikrobiologiczny przyśpieszający rozwój mikroflory glebowej [Informacja końcowa z realizacji projektu… 2015]. Można znaleźć wiele potwierdzeń w literaturze odziaływania kwasów humusowych, powodujących zwiększenie i poprawę cech jakościowych plonu, np. buraka cukrowego [Rombel-Bryzek i Pisarek 2017, Wilczewski i in. 2018], ziemniaka [Matysiak 2020], pszenicy twardej [Pačuta i in. 2021].

Biostymulatory zawierające aminokwasy

Preparaty zawierające pojedyncze aminokwasy oraz hydrolizaty białkowe (mieszaniny peptydów i aminokwasów) zaliczane są do biostymulatorów białkowych [Calvo i in. 2014]. Produkty mające w swoim składzie aminokwasy wpływają stymulująco na wzrost i rozwój roślin zarówno w sposób bezpośredni [Souri 2016], jak i pośredni [Radkowski i in. 2018, Khan i in. 2019] m.in. przez poprawę efektywności pobierania i wykorzystywania składników pokarmowych przez roślinę uprawną [Souri 2016, Wang i in. 2019]. Zastosowanie aminokwasów utrzymuje korzystne pH w komórce roślinnej dzięki ich budowie buforowej [Radkowski i in. 2018]. Biostymulatory zawierające aminokwasy powodują lepszy wzrost roślin, szczególnie w niesprzyjających warunkach klimatycznych, przez zwiększenie tempa biosyntezy chlorofilu i poprawę efektywności fotosyntezy [Shams i in. 2016].

Jak podaje Rosa i in. [2024] zastosowanie mieszaniny aminokwasów (L-glutaminanu, L-tryptofanu oraz L-tryptofanu i L-glutaminu) zwiększyło udział korzeni handlowych marchwi uprawnej w plonie ogółem (średnio od 95,1% do 97,2% oraz do 98,2%) w porównaniu z kontrolą (średnio 90,7%). Najlepsze rezultaty w tym samym doświadczeniu uzyskano po aplikacji doglebowej i dolistnej L-tryptofanu i L-glutaminu – udział plonu handlowego korzeni w plonie ogólnym wzrósł do 99,6%. Badania Pipiak i Skwarek [2020] potwierdzają wzrost akumulacji azotu w roślinach nawożonych preparatami aminokwasowymi, co przekłada się na zwiększenie biomasy pędów i korzeni oraz liczby i masy owoców pomidora, winorośli i papai.

Biostymulatory zawierające ekstrakty z alg morskich

Algi brunatne w preparatach dolistnych stosowane są głównie jako regulatory wzrostu i rozwoju roślin, rzadziej jako źródła substancji pokarmowych. Dodatkowo wykazują one korzystne oddziaływanie na glebę i mikroorganizmy w niej żyjące [Arioli i in. 2015]. Chociaż ich korzystne działanie było wielokrotnie udowadniane naukowo [Drobek i in. 2019, Janas 2023], to nadal trwają prace nad poznaniem mechanizmów ich działania [Rudawska i in. 2018]. Potwierdzono pozytywny wpływ stosowania biostymulatorów z dodatkiem alg na wielkość i jakość plonu w uprawie: fasoli [Szparaga i in. 2019, Kocira i in. 2020], pszenicy twardej [Pačuta i in. 2021], marchwi nasiennej [Janas 2023], pietruszki nasiennej [Janas 2024]. Frioni i in. [2018] nie obserwowali natomiast korzystnego wpływu alg na wielkość plonu winorośli. Skuteczność biostymulatorów na bazie alg morskich badana była także w uprawie ziemniaków, gdzie stwierdzono m.in. wzrost plonu ogólnego, przyrost świeżej i suchej masy roślin, zwiększenie wysokości roślin oraz liczby łodyg [Prajapati i in. 2016].

Biostymulatory zawierające mikroorganizmy

Odrębną grupę biostymulatorów stanowią preparaty, do których produkcji wykorzystuje się żywe mikroorganizmy (tj. bakterie i grzyby), wpływające na plonowanie i wzrost roślin uprawnych [Grzyb i in. 2019]. Te produkty są badane i stosowane coraz częściej jako biostymulatory, poprawiające pobieranie, translokację i akumulację składników pokarmowych [Krawczyk i in. 2015, Grzyb i in. 2019]. Dlatego też są włączane do zrównoważonego rolnictwa zarówno w Polsce, jak i na świecie [Preininger i in. 2018].

Pozytywny wpływ na roślinę [Janas 2023] i glebę mają różne grupy mikroorganizmów, tj. grzyby, wirusy i bakterie [Krawczyk i in. 2015, Preininger i in. 2018, Chiaiese 2018]. Są to np. bakterie *Azotobacter* (wiążące wolny azot atmosferyczny i udostępniające go roślinom) czy bakterie fosforowe, np. *Bacillus megaterium* (udostępniające fosfor z form uwstecznionych do form przyswajalnych dla roślin) [Gawroński 2021]. Badania potwierdzają, że produkty zawierające mikroorganizmy wpływają korzystnie na plonowanie upraw rolniczych, np. ziemniaka [Maciejczak i in. 2023] czy pszenicy jarej [Kowalska i in. 2020].

PODSUMOWANIE

Azot jako najważniejszy pierwiastek warunkujący jakość i wielkość plonowania każdej rośliny uprawnej powinien być dostarczany roślinie w sposób racjonalny, tak aby umożliwić maksymalne wykorzystanie jego zasobów przez roślinę i nie dopuścić do gromadzenia jego nadmiaru w profilu glebowym. Pomimo iż forma mineralna azotu jest najwygodniejsza technologicznie oraz pozwala precyzyjnie zaplanować i zastosować odpowiednią dla uprawianego gatunku dawkę tego pierwiastka, w praktyce rolniczej poszukuje się alternatywnych metod prowadzących do zwiększania plonowania.

Właściwy poziom nawożenia mineralnego warunkuje dobry wzrost roślin i wysokie plony, jednak z uwagi na potencjalne przenikanie nadmiaru azotu z nawozów mineralnych do gleby i wód gruntowych dąży się do redukcji stosowania nawozów mineralnych. Ma to na celu przywrócenie zdrowej równowagi ekosystemów, przez ograniczenie zanieczyszczeń środowiska pochodzących m.in. z sektora rolniczego.

Alternatywą dla azotu mineralnego może być aplikacja tego pierwiastka przez użycie np. nawozów naturalnych (tj. obornik, gnojówka, gnojowica), organicznych, pochodzących z odpadów lub poprzez dobór odpowiedniego przedplonu (tj. rośliny wiążące wolny azot z powietrza atmosferycznego, które po przyoraniu stanowią cenne źródło azotu dla rośliny następczej). Innym sposobem zwiększenia plonowania jest modyfikacja metabolizmu rośliny poprzez stymulację wzrostu i rozwoju rośliny uprawnej. Służą do tego preparaty spełniające definicję biostymulatora, zawierające np. kwasy humusowe, glony, aminokwasy, a także żywe mikroorganizmy (tj. bakterie i grzyby).

Dobór tych metod uzależniony jest od fizjologii i specyfiki poszczególnych gatunków roślin uprawnych oraz od zasobów, jakimi dysponuje producent rolny. Ważne, aby rolnicy mieli świadomość alternatywy do stosowania azotowych nawozów mineralnych, które nie w pełni wykorzystane przez roślinę uprawną mogą być wymywane w głąb profilu glebowego lub do wód gruntowych. W efekcie przyczyniają się do degradacji środowiska naturalnego, które jest miejscem bytowania wszystkich żywych organizmów.

Producenci żywności dostrzegają konieczność dostosowania się do potrzeb konsumentów i ochrony środowiska naturalnego, dlatego też należy w przyszłych zadaniach uwzględnić poszerzenie badań nad innymi sposobami nawożenia niż mineralne.

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Abstract. Nitrogen is the most critical nutrient influencing both the quality and quantity of crop yield. It should be supplied in a rational manner to ensure its optimal uptake by plants while preventing excess accumulation in the soil profile. Although the mineral form of nitrogen is the most technologically convenient and allows for precise dosing tailored to the needs of specific crop species, its potential to leach into soil and groundwater has prompted the search for alternative yield-enhancing strategies in agricultural practice. This paper discusses the role of nitrogen in plant nutrition and its impact on soil health. It also presents alternative methods to mineral nitrogen fertilization, (including the use of organic, natural, and waste-derived fertilizers, as well as the cultivation of nitrogen-fixing pre-crop plants) additionally, it explores approaches for modifying plant metabolism through biostimulation with products containing humic acids, algae extracts, amino acids, and microorganisms. Reducing the accumulation of agriculture-derived pollutants in the natural environment is crucial for restoring the biological balance of ecosystems.

Keywords: nitrogen, crop yield, fertilization, biostimulants

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