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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

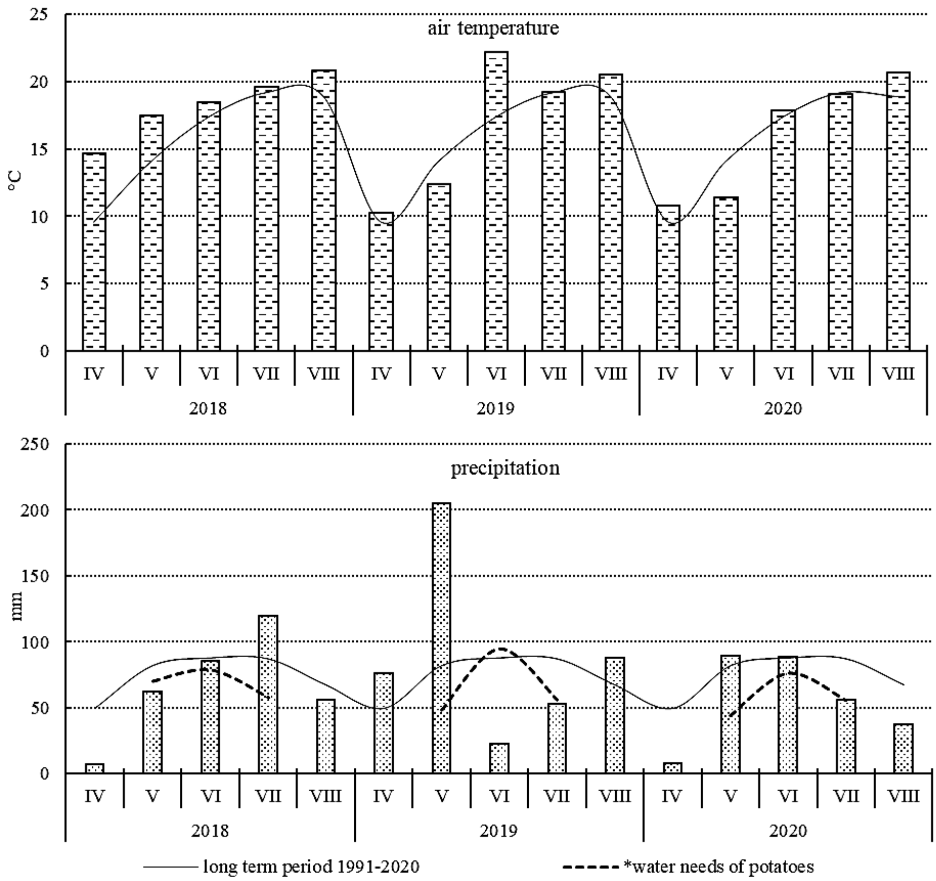
The study was carried out in 2018–2020 at the Experimental Station in Prusy (50°07'N and 20°05'E) belonging to the University of Agriculture in Kraków. The field experiment was established in a randomized sub-block (split-plot) arrangement in 3 repetitions. The plot on which the experiments were conducted 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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