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Effect of Farming System and Irrigation on Nutrient Content and Health-Promoting Properties of Carrot Roots

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Abstract: The field experiment on growing carrots included I. an organic system without pesticides and mineral fertilization of NPK; a conventional system involving NPK fertilization and pesticides in 100% doses; an integrated system, with doses of NPK and pesticides reduced by 50%; and II. the irrigation of carrot crops, with 1. no irrigation as the control, 2. two irrigations, and 3. multiple irrigations. It was proved that the integrated system had the most beneficial effect on the content of L-ascorbic acid (4.5% and 12%), carotenoids (8–10%), and dietary fiber (higher by 2.19–3.37 p.p.) than that recorded in the conventional and organic system in carrot roots. Moreover, the carrot in the integrated system had the best parameters for O-dihydroxyphenols, selenium, and the total antioxidative potential of the raw material. Organic farming, in turn, resulted in the lowest content of nitrates (2.6 times smaller than in the conventional system) and the lowest total sugar content in carrot roots (4.94 mg 100 g^{-1}), which is 20% smaller than in the integrated system), but it also caused the lowest root yield (39.02 t ha^{-1}). The conventional farming system generated the largest amount of nitrates in the raw material (170.68 mg NO_3 kg^{-1}). The irrigation of carrot plantations, regardless of the farming system, improved the nutritional composition of carrot roots by an average of about 0.94 p.p. (dietary fiber), 27% (total sugars), 15% (selenium), 29% (O-dihydroksyphenols), and 8.4% (L-ascorbic acid) and the antioxidative properties of the raw material. Multiple irrigations turned out to be the optimal variant for producing a high carrot root yield, especially in the conventional system (58.74 t ha^{-1}).

Keywords: carrot; conventional system; integrated system; organic system; irrigation; yielding; root quality

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1. Introduction

Due to its taste, versatile use, and high biological value of the edible part, the carrot (*Daucus carota* L.) is one of the most commonly cultivated and economically viable vegetable species in the world. Its nutritional value is primarily due to the high contents of carotenoids (vitamin A precursors), vitamin B, PP, dietary fiber, folic acid, and protein, as well as its natural antioxidative properties, which are essential for the human body [1–3]. Given its antifungal, anti-inflammatory, antibacterial, and anticarcinogenic properties, carrots are of high medicinal value as well. The fresh mass of carrots has a low glycemic index because the carbohydrates in carrots are digested more slowly, and therefore, the blood sugar level rises slowly. It is therefore suitable for people with diabetes problems. Carrots are vegetables with high properties for accumulating nitrates. The use of nitrogen fertilizers in conventional crops has a significant effect on the level of these compounds in crops. The

availability of such raw materials in the times of the increasing incidence of lifestyle-related diseases is particularly important for consumers, who pay special attention to the quality of products intended for consumption [4].

The nutritional value and safety of food products depend to a large extent on the quality of the raw material. The yield and chemical composition of carrot roots are affected by cultivar-specific factors, as well as by soil, climatic (amount of available water), and agrotechnical conditions during cultivation [5]. Carrot production technologies differ depending on the production region, soil quality, and potential quality of the harvested crops (conventional and organic production); hence, they also differ in various consumption of production means [6,7].

Climate changes increasingly affect agricultural management practices (management systems), whereas adaptation to rising temperatures and limited access to water is necessary to maintain the profitability of farms and, above all, to ensure the continuity of food production [8,9]. Modern plant cultivation entails a variety of methods and technologies (e.g., soil moisture sensors and crop irrigation systems) harnessed to optimize agrotechnical treatments and reduce the negative impact of the environment [10].

Water stress poses a particularly serious challenge in carrot cultivation, as it leads to reduced yields and inefficient water use by plants [11]. Due to the high economic value of carrots, irrigation planning and management should be adopted to ensure maximum yields. The irrigation of crop fields is a process of providing plants with water to offer them optimal conditions for growth and development. This is particularly important when precipitation is insufficient to cover the basic water demands of plants, which are necessary for photosynthesis, nutrient uptake, and maintaining proper plant metabolism [12]. Crop irrigation aims to ensure optimal conditions for plant development, whereas its efficiency depends on the intensity and number of treatments performed in individual farming systems (conventional, sustainable, and ecological) [13].

The extent of production specialization and the use of technological solutions in individual agricultural systems is mainly driven by their production targets [14]. Conventional carrot cultivation based on the high consumption of synthetic mineral fertilizers and chemical plant protection products is common in many countries. It ensures high yields but is also associated with many threats posed to the natural environment and consumer health. Conventional agriculture is largely responsible for the degradation of the natural environment, as well as for the accumulation of too many undesirable substances in agricultural crops [15,16]. With this in mind, more environmentally friendly systems have been developed in recent years, such as integrated and organic systems [17,18]. In the integrated system, the use of nitrogen fertilization is usually reduced by 30–40% compared to the high-input conventional system, where fertilizer doses are adjusted to the needs of the crops. Plant protection treatments are applied depending on the agent's recommended dose for a specific pathogen [19]. Organic farming uses only natural methods and means of production to produce high-quality food while maintaining the biological homeostasis in the natural environment [20–22]. In organic farming, the problem may be the removal of nutrients from the soil, but this process can be reduced by using natural fertilizers, improving the soil structure, and using appropriate crop rotations [23]. In organic plant production, the basis for fertilization includes natural fertilizers such as manure, liquid manure, a slurry, and fertilizers of plant origin (vermicompost, catch crops for plowing in, plant waste, bone meal, and fish waste). Mineral fertilizers are also allowed, but only in the form of ground minerals that have not been subjected to chemical processes. They are a fundamental source of nutrients for cultivated plants [24]. Although the rate of release of nutrients from organic fertilizers is slow compared to chemical fertilizers [25], they significantly improve the growth and quality of crops [26]. Crop yields from organic

farming are often lower than those from conventional or sustainable farming, as are crop quality [27]. However, some studies indicate that they tend to equal or exceed them over time, especially under drought conditions or on degraded soils [28].

The aim of the undertaken study was to determine the yield of carrots and the selected quality parameters of its roots, with particular emphasis on health-promoting values, depending on three farming systems (conventional, integrated, and organic) and the level of drip irrigation of crops (multiple, double, and no irrigation). A research hypothesis was advanced that the most beneficial farming system for carrots would be the integrated system because it would ensure the best nutritional and health-promoting value of its raw material (roots), with satisfactory productivity, which is not significantly different from that recorded in the conventional system. It was also assumed that the best production and quality effects of carrot roots would be ensured using multiple irrigations due to the indications of moisture sensors placed in the soil, which monitor the water needs of this plant.

2. Materials and Methods

2.1. Experiment Design and Field Management

A field experiment was conducted in the years 2020–2022 at the Czesławice Experimental Farm (51°30′ N; 22°26′ E, Lubelskie Voivodeship, Poland). The experiment was set up as a split-block design in 3 replicates, and the area of a single plot was 10 m^2 (2 m × 5 m). The total area of the experiment (27 plots) was 270 m^2. It was located on a loess-derived Luvisol, with the grainsize distribution of silt loam (PWsp) classified as a good wheat soil complex (soil class II). The carrot of the 'Kinga' cultivar, which was intended for food processing, was the test plant.

In each study season, experimental plots (with the carrot cultivated in conventional, integrated, and organic systems) were randomly located in different parts of the field. Before the establishment of the experiment (the autumns of 2019, 2020, and 2021), the soil was characterized by a medium amount of available macronutrients (Table 1).

Table 1. Characteristics of the soil before establishing the experiment in the subsequent study years *.

Specification	2019	2020	2021	(HSD $p \geq 0.05$)
Organic C (%)	0.85	0.87	0.86	n.s.
Total N (%)	0.10	0.09	0.09	n.s.
P (mg kg^{-1})	128.2	127.3	127.9	n.s.
K (mg kg^{-1})	216.8	217.2	218.1	n.s.
Mg (mg kg^{-1})	68.3	67.5	67.8	n.s.
Se (μg kg^{-1})	0.382	0.379	0.385	n.s.
Soil pH (1M KCl)	6.5	6.5	6.5	n.s.

* The methodological assumption was that the input nutrient composition of the soil under the plots with the organic, integrated, and conventional system was the same in each year of the study in order to objectively assess the impact of agricultural technology in the individual farming systems (NPK fertilization levels and pesticide) and the level of irrigation on the assessed quality parameters of carrot roots; n.s.—not significant.

Two experimental factors were analyzed:

I. Farming system
   - A. organic—without chemical plant protection agents and NPK fertilization
   - B. conventional—with the use of chemical plant protection agents and NPK fertilization in the available assortment and in full 100% recommended doses for a given plant species.

C. integrated—with the sustainable use of chemical plant protection agents and NPK fertilization, where doses are reduced by 50%.

II. Crop irrigation

1. no irrigation as the control.
2. double irrigation (at the beginning of crop vegetation, namely at the 2–3-leaf stage and at the stage of critical demand for water, which are the early stages of storage root development).
3. multiple irrigations (occasional) resulting from monitoring the drought condition in the field *.

* Sensors installed in 3 randomly selected locations on each plot (measuring soil moisture at 2 soil levels, i.e., 0–15 cm and 15–25 cm) continuously monitored the water content of the soil. This allowed us to determine whether there was enough water for carrot plants in a given growing period and established the irrigation level needed. Before placing the sensors in the soil, a hole was dug in which the sensor was installed; then, the sensor was covered with soil to the full depth at which it was installed. The sensors were continuously monitored for their efficiency, and soil moisture readings were taken.

Carrot irrigation consisted of evenly distributing water through a tubular irrigation system (drip irrigation). Water consumption in the irrigation system was similar in the individual study years due to similar meteorological conditions and the resulting water content of the soil monitored by the soil moisture sensors (Table 2).

Table 2. List of irrigation procedures during carrot vegetation.

Specification	The Amount of Irrigation in Each Year of the Study (L Water ha^{-1})		
	2020	2021	2022
Double irrigation	300,000 250,000	280,000 260,000	310,000 300,000
Irrigation in total	550,000	540,000	610,000
Multiple irrigation	300,000 150,000 250,000 250,000 200,000 150,000	280,000 160,000 260,000 240,000 180,000 160,000	310,000 140,000 250,000 260,000 210,000 140,000
Irrigation in total	1,300,000	1,280,000	1,310,000

'Kinga' is an early carrot variety (110 days of the vegetation period) of the 'Natlejski' type; it shows high tolerance to high temperatures and is resistant to powdery mildew. The root length of this variety is about 18–20 cm. The root is uniformly colored, intensely orange, and regularly cylindrical. The purpose of carrot variety 'Kinga' is as follows: fresh markets (bunch harvest), processing, and especially preserves for children (accumulates little nitrates).

In each study year, carrot seeds were sown into soil in the third decade of April by means of a pneumatic point seeder in the amount of 4.5 kg ha^{-1} (corresponding to a sowing density of 1.2 million seeds ha^{-1}) in a row spacing of 30 cm at a depth of 1 cm. Spring barley was sown each year as the previous crop. Carrots were grown in the conventional (plowing) tillage system.

Taking into account the initial availability of nutrients in the soil (determined per hectare), which was similar in all study years, pre-sowing fertilization was applied in doses shown in Table 3.

Table 3. Fertilization applied in individual farming systems.

Farming System	Mineral Fertilization in kg ha^{-1}		
	N	P	K
Organic *	-	-	-
Integrated	45	30	75
Conventional	90	60	150

* In the organic system, no fertilization allowed was applied in this system, which enabled the precise capturing of the effect of full and 50% reduced doses of NPK mineral fertilizers (in the conventional and sustainable system) on the yield quality of the test plant (carrot). NPK mineral fertilization was applied in the ratio of 1:0.6:1.6. Mineral fertilization with N was applied in the form of 34% ammonium nitrate, 17% nitrogen (N) in its nitrate form (NO_3), and 17% nitrogen (N) in its ammonium form (NH_4), and P was applied in the form of 46% granulated triple superphosphate (in the P_2O_5 form), while K was applied in the form of 60% potassium salt (in K_2O form).

The following chemical plant protection treatments were applied in carrot crops in the conventional system (100% doses). Before sowing, carrot seeds were dressed with Marshal 250 DS (a.s. carbosulfan) to protect them against diseases (in a dose of 70 g kg^{-1} of seeds), followed by Stomp Aqua 455 CS herbicide (a.s. pendimethalin) in a dose of 3 L ha^{-1}, which was applied 5 days after sowing for chemical weed control, and Amistar 250 SC fungicide (a.s. azoxystrobin) in a dose of 1 L ha^{-1}, which was applied at the 6-leaf stage of carrot development. No insecticides were applied because no significant occurrence of pests in carrot crops was recorded in each of the growing seasons. In the integrated system, 50% doses of analogous plant protection agents were applied at the same time points as in the conventional system.

Weed eradication was performed twice in all farming systems: (1) inter-row mechanical weeding in the stage of 3–5 true carrot leaves and (2) manual weeding before closing the rows. Each year, carrots were harvested in the second decade of September.

2.2. Plant Sampling, Measurement, and Chemical Analyses of Carrot Root Grain

The total yield and marketable yield of carrots were determined according to the EC regulation [29] while taking account of deformed and diseased roots. The marketable yield of carrot roots was then referred to as the area size of 1 ha and expressed in t ha^{-1}. After root selection from the marketable crop yield, 20 roots were selected from each plot for chemical analyses.

The carrot roots were determined for dry matter content after heating to a temperature of 105 °C, according to the Polish Standard in 30 min [30]; L-ascorbic acid content with Tillmans' method in Pijanowski's modification [31,32]; total sugar content with the Luff–Schroorl method [33,34]; and total carotenoid content with the spectrophotometric method in a petroleum ether extract on a Spectroquant PHARO 100 spectrophotometer (Merck, Darmstadt, Germany) at a wavelength of λ = 445 nm. Acetone was used as the extraction reagent [35], and total carotenoid content was calculated according to the method by Biehler et al. [36]; total dihydroxyphenol content was determined with the spectrophotometric method at a wavelength of λ = 725 nm (Shimadzu 1800 spectrophotometer, Shimadzu Corp. Kyoto, Japan), and it was expressed in caffeic acid equivalents. To perform the measurement on the spectrophotometer, 50 µL–500 µL of the extract (depending on the expected absorption value of the analyzed sample) was added and transferred to a volumetric flask. A total of 2.0 mL of methanol, 10 mL of H_2O, 2 mL of Folin's reagent, and 1.0 mL of a 10% Na_2CO_3 solution were added. The samples were left for 0.5 h and then filled up with deionized water, and the measurement was performed on the spectrophotometer at a wavelength of λ = 725 nm and compared to the reference sample [37]; total dietary fiber content was measured with the gravimetric enzymatic method using the Fibertec 2010 system (FOSS, Hillerød, Denmark). Samples were digested with the following enzymes: thermostable alpha-amylase, pepsin, and pancreatin. Then, the mass

of the undigested residue was determined; the supernatant containing soluble dietary fiber was precipitated from the solution, and its mass was determined. Mineral analysis of the isolate was performed by means of atomic absorption spectrometry using a VarianSpectra A 280 FS spectrophotometer (Varian, Inc., Palo Alto, CA, USA) [38]; selenium (Se) content was determined using an ICP-OES spectrometer (Prodigy, Leeman Labs, New Hampshire, MA, USA) after extraction with tetramethylammonium hydroxide (TMAH, Sigma-Aldrich Co. LLC, St. Louis, MO, USA), in accordance with the procedures specified in the Polish and European Standards [39]; the total antioxidative potential of β-carotene and linoleic acid in the conjugated system was measured [40,41]. β-carotene (95%, Sigma-Aldrich) was dissolved in chloroform, and the resulting solution was mixed with linoleic acid (95%, Sigma-Aldrich) and Tween 40 (poly-oxyethylene sorbiton palmitate) as an emulsifier. The resulting β-carotene/linoleic acid emulsion was added to the methanol–acetone extracts and incubated at 50 °C. The degree of β-carotene oxidation was determined by measuring the absorbance at 470 nm against the emulsion prepared without added β-carotene. Antioxidative activity (AA) was expressed as a percentage of β-carotene oxidation inhibition relative to the control [42]; nitrate (NO_3) content was determined with the spectrophotometric method [43].

2.3. Statistical Analyses

The study results were analyzed statistically using the Statistica PL 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA). The significance of differences was verified with Tukey's honestly significant difference (HSD) test at the level of $p \geq 0.05$.

Before applying the analysis of variance, the Shapiro–Wilk normality test was performed; it was used to check whether the analyzed data came from a distribution close to normal, and it was found that the assumption of a normal distribution was met before performing parametric tests. The results were presented in tables as the mean values from 3 years of research because no statistically significant differences were found between the individual research seasons (2020–2022). Tables 4 and 5 present significant interactions between the experimental factors (farming system × level of irrigation). In addition, the standard deviations of the results (SD ±) were provided for all features included in the tables.

Table 4. Root yields and content of nutrients in carrot roots, with means from 2021 to 2023.

Specification	Marketable Yield of Carrot Roots (t ha^{-1}) *	Dry Matter Content (%)	Total Dietary Fiber Content (%)	Carotenoid Content (mg 100 g^{-1})	Total Sugar Content (mg 100 g^{-1})	Selenium Content (µg kg^{-1})
Farming system (FS)						
Organic	39.02 (±0.09) b	12.42 (±0.08) b	7.53 (±0.05) c	16.36 (±0.09) b	4.94 (±0.05) c	17.43 (±0.10) c
Integrated	51.29 (±0.10) a	13.76 (±0.10) a	11.26 (±0.09) a	18.14 (±0.12) a	6.10 (±0.07) a	20.73 (±0.12) a
Conventional	53.93 (±0.11) a	13.74 (±0.09) a	9.07 (±0.06) b	16.64 (±0.08) b	5.72 (±0.07) b	19.37 (±0.11) b
Carrot irrigation (CI)						
NI	45.07 (±0.12) b	12.40 (±0.07) b	8.29 (±0.07) b	16.57 (±0.07) a	5.29 (±0.06) b	16.93 (±0.09) c
2I	47.83 (±0.13) b	13.40 (±0.08) a	9.23 (±0.07) a	17.09 (±0.09) a	5.57 (±0.04) a	18.63 (±0.11) b
MI	51.36 (±0.10) b	13.79 (±0.09) a	9.32 (±0.08) a	17.30 (±0.10) a	5.80 (±0.05) a	21. 97 (±0.10) a
Factor interaction						
FS	**	**	**	**	**	**
CI	**	**	**	n.s.	**	**
FS × CI	**	n.s.	**	**	**	**

Table 4. *Cont.*

Specification		Marketable Yield of Carrot Roots (t ha^{-1}) *	Dry Matter Content (%)	Total Dietary Fiber Content (%)	Carotenoid Content (mg 100 g^{-1})	Total Sugar Content (mg 100 g^{-1})	Selenium Content (µg kg^{-1})
Effect of the farming system and carrot irrigation interaction on the yield and content of nutrients							
OS	NI	37.02 (±0.09) f	12.07 (±0.05) a	7.03 (±0.03) a	15.37 (±0.05) a	4.66 (±0.03) e	15.50 (±0.07) a
	2I	38.97 (±0.10) e	12.36 (±0.06) a	7.50 (±0.04) b	16.56 (±0.06) b	4.93 (±0.04) d	16.70 (±0.08) b
	MI	41.12 (±0.12) d	12.44 (±0.07) a	7.55 (±0.05) b	16.75 (±0.06) b	5.13 (±0.04) c	20.10 (±0.08) e
IS	NI	48.11 (±0.11) c	13.88 (±0.08) a	9.95 (±0.06) e	17.90 (±0.07) c	5.89 (±0.03) b	17.80 (±0.06) c
	2I	51.55 (±0.13) bc	13.81 (±0.07) a	11.27 (±0.05) f	18.15 (±0.08) d	6.02 (±0.04) b	19.80 (±0.05) d
	MI	54.23 (±0.12) b	14.02 (±0.09) a	11.25 (±0.05) f	18.26 (±0.08) d	6.35 (±0.05) a	24.60 (±0.10) g
CS	NI	50.08 (±0.10) c	13.96 (±0.08) a	7.88 (±0.03) b	16.45 (±0.05) b	5.33 (±0.03) c	17.50 (±0.06) c
	2I	52.98 (±0.13) b	14.01 (±0.09) a	8.93 (±0.05) c	16.56 (±0.06) b	5.77 (±0.04) bc	19.40 (±0.08) d
	MI	58.74 (±0.14) a	14.36 (±0.10) a	9.16 (±0.06) d	16.88 (±0.07) bc	5.93 (±0.05) b	21.20 (±0.09) f

* Marketable yield of carrot roots computed after deducing the content of small, diseased, and deformed roots from the total root yield. Different letters (a–g) denote a significant difference (HSD $p \geq 0.05$) according to ANOVA and Tukey's test; **—significant difference; ±SD—standard deviation. NI—no irrigation, 2I—double irrigation, and MI—multiple irrigation. OS—organic, IS—integrated, and CS—conventional; n.s.—not significant.

Table 5. Antioxidative activity and contents of O-dihydroxyphenols, L-ascorbic acid, and nitrates in carrot roots, with means from 2021 to 2023.

Specification		Antioxidative Activity (%) in the β-Carotene/Linoleic Acid System	O-Dihydroxyphenol Content (g 100 g^{-1})	L-Ascorbic Acid Content (mg 100 g^{-1})	Nitrate Content (mg NO_3 kg^{-1})
Farming system (FS)					
Organic		51.53 (±0.13) b	18.37 (±0.08) b	7.06 (±0.02) b	65.72 (±0.14) c
Integrated		60.25 (±0.15) a	24.28 (±0.07) a	7.97 (±0.04) a	117.78 (±0.17) b
Conventional		59.10 (±0.14) a	23.48 (±0.06) a	7.70 (±0.03) a	170.68 (±0.16) a
Carrot irrigation (CI)					
NI		54.56 (±0.12) b	18.39 (±0.08) c	7.16 (±0.02) b	131.17 (±0.18) a
2I		59.37 (±0.10) a	25.70 (±0.10) a	7.58 (±0.03) a	120.51 (±0.17) b
MI		57.72 (±0.10) ab	23.12 (±0.11) b	7.81 (±0.04) a	106.10 (±0.15) c
Factor interaction					
FS		**	**	**	**
CI		**	**	**	**
FS × CI		**	**	**	**
Effect of the farming system and carrot irrigation interaction on the content of nutrients					
OS	NI	48.70 (±0.09) f	16.30 (±0.06) g	6.73 (±0.03) a	75.77 (±0.15) e
	2I	54.37 (±0.12) e	20.43 (±0.06) d	7.02 (±0.03) b	66.43 (±0.14) f
	MI	52.73 (±0.11) c	18.90 (±0.05) f	7.32 (±0.02) b	58.07 (±0.14) g
IS	NI	58.20 (±0.12) d	19.30 (±0.04) e	7.30 (±0.02) b	135.83 (±0.18) cd
	2I	62.30 (±0.13) a	29.27 (±0.06) a	8.00 (±0.03) d	120.57 (±0.17) c
	MI	60.40 (±0.12) b	25.40 (±0.06) c	8.26 (±0.05) d	102.10 (±0.15) d
CS	NI	56.77 (±0.10) cd	19.57 (±0.08) e	7.44 (±0.03) bc	181.90 (±0.19) a
	2I	61.43 (±0.13) a	27.40 (±0.07) b	7.70 (±0.03) c	174.53 (±0.18) a
	MI	60.03 (±0.12) b	25.07 (±0.06) c	7.86 (±0.05) c	158.13 (±0.16) b

Different letters (a–g) denote a significant difference (HSD $p \geq 0.05$) according to ANOVA and Tukey's test; **—significant difference; ±SD—standard deviation. NI—no irrigation, 2I—double irrigation, and MI—multiple irrigation. OS—organic, IS—integrated, and CS—conventional.

3. Results

The marketable yield of carrot roots was significantly affected by both experimental factors and their interaction. Regardless of irrigation, it was the lowest in the organic system, being ca. 24% and 28% lower than in the integrated system and conventional system, respectively. Noteworthy is a statistically insignificant difference (reaching only 4%) in carrot root yield between the conventional and integrated systems. Regardless of the farming system adopted, the multiple irrigations of the carrot crop contributed

to a significant increase in root yield compared to double irrigation (by ca. 7.5%) and especially to the variant without irrigation (by ca. 12%). Thus, it may be concluded that the double irrigation of carrot crops proved insufficient to achieve significantly higher root productivity, compared to the no-irrigation variant (Table 1). A significantly higher marketable yield of carrot roots (58.74 t ha^{-1}) was determined upon the influence of the conventional system × multiple irrigation interactions. In turn, the lowest root yield (37.02 t ha^{-1}) was produced as a result of the organic system × the no-irrigation interaction (Table 4).

Regardless of the irrigation variant, the organic system caused a significantly lower (by c.a. 1.33 percentage point (p.p.)) dry matter content of carrot roots, compared to the integrated and conventional systems. In turn, the no-irrigation variant resulted in a significantly lower dry matter content of roots by 1.0 p.p compared to double irrigation and by 1.39 p.p. compared to the multiple-irrigation variant, regardless of the farming system (Table 4).

The farming system was observed to significantly modify the total dietary fiber of carrot roots, with statistically the highest content noted in the conditions of the integrated system (higher by 2.19 p.p. compared to the conventional system and by 3.37 p.p. compared to the organic system). The irrigation of carrot crops caused a significant increase in the total dietary fiber compared to the no-irrigation variant, i.e., by 0.94 p.p. in the double-irrigation variant and by 1.03 p.p. in the multiple-irrigation variant (Table 4). A significantly lower total dietary fiber content of carrot roots was determined in the no-irrigation variant in the organic system (Table 4).

In the soil and climatic conditions of the experiment, the integrated system contributed significantly to the highest content of carotenoids in the roots of the tested carrot variety, specifically by ca. 10% and 8% compared to the organic and conventional systems, respectively. Regardless of the farming system, carrot crop irrigation (in both the double and multiple variants) caused only a tendency (statistically insignificant) for a higher carotenoid content of carrot roots (Table 4). Significantly, the lowest carotenoid content (only 15.37 mg 100 g^{-1}) was determined in the conditions of the organic system × the no-irrigation interaction (Table 4).

The most beneficial total sugar content of carrot roots was achieved in the conditions of the integrated system; that is, it was significantly higher by nearly 20% compared to the organic system and by ca. 6% compared to the conventional system. The double irrigation of carrot stands increased the total sugar content of the roots by ca. 5% compared to the control variant (no-irrigation) and by ca. 9% compared to the multiple-irrigation variant (Table 4). Significantly, the highest content of total sugars of carrot roots (6.35 mg 100 g^{-1}) was determined in the variant with multiple carrot irrigations in the integrated system, whereas significantly, the lowest one (4.66 mg 100 g^{-1}) was observed in the no-irrigation variant in the organic system (Table 4).

The content of selenium in carrot roots was significantly determined using both experimental factors and their interactions. The Se content of carrot roots harvested from plots in the integrated system was ca. 6.5% higher compared to the roots harvested in the conventional system and especially compared to those from the organic system (by ca. 16%). Regardless of the farming system, multiple irrigations of carrots contributed to Se content increase by ca. 15% compared to double irrigation and ca. 23%, especially, compared to the control variant (no-irrigation) (Table 4). Significantly, the highest selenium content of carrot roots was determined in the conditions of the integrated system × the multiple-irrigation interaction (24.60 μg kg^{-1}), whereas significantly, the lowest one was observed in the conditions of the organic system × the no-irrigation interaction (only 15.50 μg kg^{-1}) (Table 4).

The antioxidative potential of carrot roots was the highest in the raw material harvested from the integrated system (60.25%) and slightly lower in that harvested from the conventional system (59.10%). The antioxidative potential of the organic raw material of carrots was significantly lower than that of the aforementioned raw materials by 7.53–8.72 p.p. Regardless of the farming system, the double irrigation of carrots caused a significantly higher antioxidative potential of carrot roots compared to the no-irrigation variant (Table 5). A significantly lower antioxidative potential of the carrot raw material was determined in the conditions of the organic system × the no-irrigation interaction (Table 5).

Both the integrated system and the conventional system had a significant effect on the increased content of O-dihydroxyphenols in carrot roots compared to the organic system, namely by ca. 25% and ca. 22%, respectively, regardless of the irrigation variant. In turn, the double irrigation of carrot crops turned out to be the most beneficial variant in this respect (O-dihydroxyphenol content higher by ca. 10% compared to the multiple irrigation variant), especially given the higher content of these compounds compared to the non-irrigated plots—a difference approximating 29% (Table 5). Significantly, the highest content of O-dihydroxyphenols was determined in the conditions of the integrated system × the double-irrigation interaction (29.27 g kg^{-1}), and significantly, the lowest one (16.30 g kg^{-1}) was seen in the conditions of the organic system × the no-irrigation interaction (Table 5).

The content of L-ascorbic acid in carrot roots was the highest in the integrated system and slightly lower in the conventional system, compared to the organic system (by ca. 12% and ca. 8.5%, respectively). Regardless of the farming system, the multiple-irrigation variant caused a higher L-ascorbic acid content of the roots (not significantly bigger because it increased only by ca. 3% compared to the double-irrigation variant), which was statistically significantly higher (by ca. 8.4%) than in the no-irrigation variant at 7.16 mg 100 g^{-1} (Table 5). Significantly, the lowest content of L-ascorbic acid in the raw material was determined in the conditions of the organic system × the no-irrigation interaction (Table 5).

Significantly, the conventional system caused the highest content of nitrates in carrot roots, which was higher by ca. 31% than in the integrated system and as much as 2.6-fold higher than in the organic system. Significantly, regardless of the farming system, no irrigation of carrot crops caused the highest content of nitrates in the roots, compared to double irrigation (a difference approximating 8.2%) and especially compared to the multiple-irrigation variant (a difference approximating 19%) (Table 5). Statistically, the lowest content of nitrates (58.07 mg NO_3 kg) was determined in the conditions of the organic system × the multiple-irrigation interaction (Table 5).

4. Discussion

4.1. The Effect of the Farming System on the Productivity and Nutritional Value of Carrot Roots

The research results obtained demonstrate that the conventional and sustainable farming systems did not cause significant differences in carrot root yield (the yield was higher by only about 4% in the conventional system). In turn, carrot cultivation in the organic system contributed to a significant reduction (by 24–28%) in its productivity compared to the other two systems. Similarly, in other studies [44], lower carrot productivity in the organic system than in the integrated system was found. Significantly, in the next experiment by [45], it was found that the root yield and total dry matter content were the highest upon the full (100%) level of nitrogen fertilization, especially in combination with optimal crop irrigation.

In the study by [46], the organic system, involving fertilization with compost, increased the marketable yield of carrot roots compared to the conventional system. The farming system had no significant effect on the contents of dry matter, minerals, and total sugars, but the quality of conventional carrots was significantly reduced by the high content of

nitrates and pesticide residues, which were not detected in organic carrots. Organic carrots, on the other hand, had a lower content of L-ascorbic acid (−24%) and β-carotene (−6%). Similar trends, namely a more beneficial effect of the organic system on the yield and quality of carrots, were noted in another series of studies [47].

It should be emphasized, however, that no organic fertilization or bio-protection of carrot crops (only mechanical weed control) was used in the organic system in the present study; hence, the productivity of carrots was lower than that obtained by other authors who used, for example, organic fertilizers or bio-pesticides.

Other studies [48] indicated that the analysis of the nutritional composition of carrots did not show any significant differences between conventionally and organically grown crops. Similarly to the present research, they found only a tendency for higher nitrate content in conventionally grown carrots. In another experiment [49], it was found that the farming system had no effect on the marketable and total yield of carrot roots. There were also no significant differences in the content of L-ascorbic acid between the carrots from various production systems. Moreover, conventionally and organically grown carrots did not differ in terms of the content of total sugars in the roots.

Other authors [50] report that carrots grown in the integrated system had higher contents of N and Mg, as well as Cu, Zn, and Mn, while organic carrot roots had more P and Fe. There is therefore no clear scientific evidence of the difference in environmental impact, nutritional quality, safety, and health impact between agricultural products (food) from conventional and organic systems. Assessing the effects of using organic instead of conventional farming is a difficult process to apply, both in terms of food quality and environmental sustainability [27]. Our own research shows that farming systems contribute to different efficiencies of absorption by the crop (carrot) of nutrients contained in the soil (e.g., nitrogen and selenium) and are particularly beneficial in the interaction between the integrated system × the optimal (multiple) irrigation of the plantation.

It should be noted that there is no doubt that organic food is safer due to the lack of pesticide residues; however, it is not entirely certain whether vegetables produced in this way are better in terms of their nutritional value (nutrient composition) than those produced in conventional and integrated systems [51]. Our research, as well as other research [52], confirms this thesis because the most favorable quality and health parameters of carrot raw material were obtained in the integrated system, followed by the conventional system (the highest content of carotenoids, total sugars, dietary fiber, and selenium), but not in the organic system.

In other experiments it was found that the content of the dry matter of carrots did not differ significantly in the roots harvested from different farming systems. The content of nitrates in the roots tested was low and accounted for 25.5–55.8% of the permissible level. The highest levels of nitrates were detected in the roots from integrated cultivation. A statistically significantly lower level of total sugars, compared to carrots from other systems, was also shown in the carrot roots from this farming system. In contrast, carrot roots from different farming systems did not differ in the contents of L-ascorbic acid and carotenoids [53]. Not observed in studies are the significant differences in the content of L-ascorbic acid in carrots grown in the conventional and organic systems [54]. Further research shows that, among the metabolites, carrot roots from the organic system had a significantly higher content of total organic acids and vitamin C compared to the integrated system, regardless of the variety tested. In addition, there were no statistically significant differences in the total content of phenolic acids in carrots from the organic and integrated systems. The farming system also had an insignificant effect on the content of carotenoids in carrot roots [55].

Other researchers have proven that the carotenoid content in carrot roots and human diets was not significantly affected by the farming system or the year of the study, despite differences in fertilization strategy and levels in these systems. The expected higher content of putatively health-promoting carotenoids in organic food products was not documented in this study. Also, the plasma carotenoid status of the studied consumers significantly increased after the consumption of the organic and conventional diets, but no significant differences were observed between the farming systems [56].

4.2. The Effect of Irrigation on the Productivity and Nutritional Value of Carrot Roots

Many authors emphasize that irrigation management aimed at improving crop yield and quality requires understanding how dry the soil can be before water stress affects plant growth dynamics and crop yield (what the yield reduction will be if water stress occurs). This study showed that the total carrot root biomass and yield decreased linearly with increasing water deficit, confirming the formulated hypothesis. The main reason for the yield reduction was the decrease in carrot root diameter. However, no significant correlation was found between maximizing irrigation and nutrient levels in carrot roots, which was also confirmed in the present study. It is indisputable, however, that minimizing water deficits is crucial for producing high carrot yields [57,58]. In the present study, the intensification of carrot irrigation significantly influenced the increase in root yield (especially in the case of multiple irrigations of carrot crops grown in the conventional system).

In studies addressing both carrot water demand and water use efficiency by plants [11,59], it was found that full irrigation (100% pan evaporation) ensured the highest fresh mass of carrot roots, compared to deficit irrigation (25% pan evaporation).

The response of carrots to additional N fertilization of 30 kg and 60 kg ha^{-1} was also studied. The higher soil moisture due to irrigation promoted nutrient uptake by carrots grown on mineral and organic soils. In highly compacted clay soil, nutrient utilization decreased with increasing soil compaction due to irrigation, while nitrate content in roots increased. Increasing the nitrogen fertilization of organic soil from 30 kg ha^{-1} to 60 kg ha^{-1} resulted in a 30% increase in NO_3-N content [60]. Similarly, in the present study, the nitrate content in carrot roots was the highest at 100% N fertilization (conventional system) and significantly decreased when a 50% reduced N dose was applied (integrated system).

The main goals of drip irrigation are to reduce water deficit near the rhizosphere, reduce evaporation, and minimize water consumption so that its applicability increases. When the level of drip irrigation is larger (100–120%), it significantly increases crop yields by 8.03–28.92%. When water resources are sufficient, increasing the level of drip irrigation also improves crop yields [61]. In addition, drip irrigation can reduce fertilizer leaching and soil salinization and thus indirectly improve the availability of plant nutrients (which was clearly confirmed by the results of our own research).

The effective management of drip irrigation strongly depends on moisture distribution [62]. Hence, the drip irrigation method applied in this experiment, which synchronized with soil moisture sensors indicating the actual water demand, ensures the most efficient use of water and its impact on increasing crop yields. Other authors [63] also mentioned that the drip irrigation system had great potential to save water and nutrients, thereby improving root yield and quality, mainly due to minimizing water deficit in the rhizosphere and reducing evaporation. It has been shown in the example of cotton that irrigation taking into account the actual water needs of plants had an immediate effect on increasing its yield by 39–46%, compared to rain irrigation [64].

The optimal irrigation schedule was important to ensure high meteorological parameters in the case of vegetables, especially in the context of information on the water content of the soil substrate, during the growing season of the crop, which was consistent

with the findings from our study. The ratio between plant biomass accumulation and water consumption underlies water use efficiency, especially in the current era of climate change [65,66].

Previous studies [67] have shown that the growth, yield, and sugar content of carrot roots were significantly dependent on the level of drip irrigation (60, 80, and 100% irrigation levels). Carrot growth parameters showed a linear relationship until the optimal (100%) soil irrigation level had been achieved. The highest carrot yield of 33.0 tons ha^{-1} was obtained at the 100% irrigation level, and the lowest yield of 18.47 tons ha^{-1} was produced at the 60% irrigation level. Importantly, carrot yields at the 60 and 80% irrigation levels did not differ significantly. It was found that carrots grown at the 80% irrigation water deficiency level had the highest sugar content. Similar correlations were found in the present study, in which the highest level of irrigation (multiple) had the most beneficial effect on carrot productivity, while the best parameters of the nutritional composition of roots were obtained with double irrigation.

In the study by [68], the results of their experiment showed a reduction in carrot yield of 13–22% and 22–32% in the 70% and 40% irrigation treatments compared to 100% irrigation. Significant differences in carrot root yield and quality depending on the level of irrigation were also observed. Yield and quality parameters decreased most upon reduced irrigation, which was accompanied by a decrease in morphological traits (plant height, number of leaves, root mass, root length, and diameter). Root quality indices, i.e., contents of L-ascorbic acid, total sugars, beta-carotene, and phenolics, were also affected by the frequency of irrigation [69].

Similarly, in the present study, the lack of irrigation, as well as irrigation optimization (multiple irrigations resulting from soil monitoring using moisture sensors), contributed significantly to the lowest and the highest productivity of carrot roots, respectively. On the other hand, the procedures of double irrigation of crops (in critical development stages for the plant) proved sufficient in affecting the quality parameters of carrot roots, regardless of the farming system.

5. Conclusions

The obtained research results confirmed the adopted hypothesis that the most favorable productivity and quality of carrot raw material were obtained in the integrated system due to the interaction with the double irrigation of crops (in critical periods of the growth and development of the crop). The marketable yield of roots in the integrated system was only 4% lower than that obtained in the conventional system, which involved 100% doses of mineral fertilization and chemical plant protection products. Sustainable carrot production consisting the use of 50% doses of NPK mineral fertilizers and half doses of pesticides, together with the double irrigation of crops, contributed to the highest contents of L-ascorbic acid, carotenoids, and dietary fiber in the roots. In addition, carrots grown in the integrated system were characterized by the best health-promoting parameters, which were expressed by the contents of O-dihydroxyphenols and selenium, as well as the total antioxidative potential of the raw material (roots).

In the conventional system, the nutritional composition and health-promoting parameters of carrot roots were worse (mostly to a significant extent) than in the integrated system. In addition, the conventional system produced the highest content of nitrates in the raw material. The organic system influenced the lowest content of the analyzed qualitative components, which can be explained by the lack of fertilization and plant protection in this system. The advantage of the organic system was the formation of a low content of nitrates in carrot roots.

Multiple irrigations of carrot crops resulting from the readings of soil moisture sensors (and therefore optimal by definition) influenced the highest productivity of carrots in each farming system and also stimulated a favorable nutritional composition of roots.

From the point of view of agricultural practices, double irrigation is sufficient and beneficial in shaping carrot quality parameters, regardless of the farming system. However, optimizing irrigation through multiple irrigations by monitoring soil moisture status has an additional impact on obtaining the highest yield of carrot roots.

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