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Requirements and Effects of Surface Drip Irrigation of Mid-Early Potato Cultivar Courage on a Very Light Soil in Central Poland

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Abstract: The purpose of this research was to determine the water needs and results of drip irrigation of mid-early potato cultivar Courage. Studies were carried out in central Poland in 2011–2013 on very light soil. The experiment was designed as two-factorial trials with four replications. The first factor was drip irrigation: O = control (without irrigation), D = drip irrigation. The second factor was the nitrogen fertilization method: P = broadcasting, F = drip fertigation. Nitrogen fertilization was 120 kg N ha^{-1} on each plot. Crop coefficients for irrigation period were 0.4 in June and 0.6 in July and August. According to calculations based on the crop coefficients and correction coefficients acc. Hargreaves^{DA} model the water requirement of potato for June–August was 202 mm. Drip irrigation increased the marketable tuber yield by 55%. Irrigation water use efficiency increased from 257 kg ha^{-1} mm^{-1} in D + P to 264 kg ha^{-1} mm^{-1} in D + F. The productivity of 1 kg of nitrogen fertilization was 189 kg ha^{-1} in control non-irrigated plots and 321 kg ha^{-1} in drip-irrigated plots, and it rose up to 337 kg ha^{-1} when fertilization was applied by fertigation.

Keywords: crop coefficients; irrigation needs; nitrogen fertigation; *Solanum tuberosum* L.; water requirement

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1. Introduction

The potato (*Solanum tuberosum* L.) is the fourth most grown plant in the world (after corn, wheat and rice) and it is an important food for humanity [1,2]. The production volume of potatoes in the world in 2018 amounted to 368 million tons. The largest producer is China with over 90 million tons, followed by India (over 48 million tons) and Ukraine (over 22 million tons). Poland is 10th place on the list of countries that produce potatoes in the highest quantity (7.5 million tons). The average potato yield in Poland is 25.14 t ha^{-1}. For comparison, China, with the highest production and cultivation area gains the yield of 16.4 t ha^{-1}, while in the USA it was 46.4 t ha^{-1} [3]. The potato is especially recognized as a source of high-quality proteins, carbohydrates, vitamin C, vitamin B6, vitamin B3, and certain minerals such as potassium, phosphorus, and magnesium. Moreover, it is a source of considerable amounts of bioactive components from the group of polyphenols, which guarantee proper antioxidant activity of this vegetable [4].

The growth and yield of potato is adversely affected by abiotic factors, such as drought [5–8]. The water needs of potatoes during the growing season are quite high, reaching from 350 mm to 450 mm of rainfall in the period from April to September in Poland [8]. This amount depends on the soil conditions in a given location and on the cultivar, as well as on the early or late maturation of the cultivar [7,9]. The period of the greatest water requirement for potatoes is the phase of tuber setting and the phase of rapid increase in tuber weight, which extends over several weeks depending on the cultivar and most often occurs in the period from June to the end of August [10].

The potato is grown in all types of irrigation systems around the world, but the best irrigation systems are those that allow for light, frequent, and even irrigation. The most precise is the drip irrigation system, which is the most modern method for irrigating plants grown in rows, including potato irrigation. At the same time, it is the friendliest to plants and the ecosystem [7,8,11–17]. Irrigation is most effective in light and very light soils [8,18–25]. Taking into account the high productivity of the potato, it is one of the most effective plant species in terms of using water for yield accumulation [26]. Supply of water and nitrogen in potato growing systems is an important factor for controlling production levels, especially in arid and semi-arid regions characterized by large irrigation requirements. Drip irrigation in combination with mineral drip fertigation is an effective method for increasing the efficiency of water use and potato yields [7,12,13,16,17,27–30]. This method of nutrient supply is more efficient compared to traditional solid fertilizer application due to the optimal nutrient concentration and high root density in the wet zone of the soil [12,13,31]. It is also a very economical method thanks to the possibility of precise fertilization doses and fast response to changing plant needs [8].

The aim of the present research was to estimate the water requirements and determine the effects of drip irrigation and nitrogen fertilization using drip fertigation of mid-early potato cultivar Courage grown on very light soil in moderate climate in central Poland. For this study, a potato cultivar was selected, for which the response to the drip fertigation treatment applied in the soil and climatic conditions existing in the present experiment had not been previously tested. The results of this study on drip irrigation and fertigation of potato—as an efficient combination in the agricultural practice—can be very useful for farmers from the countries of Central and Eastern Europe, especially during the drought periods. Common use of fertigation in agricultural practice can reduce the risk of environmental contamination. On the other hand, the widespread usage of the drip system may contribute to the protection of limited water resources. The results of the study can demonstrate that the drip irrigation system is an effective factor for drought mitigation during the vegetation period of crops such as potato from the perspective of climate change.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted under temperate climate conditions in the central part of Poland (Kruszyn Krajeński near Bydgoszcz) (53°04′53″ N, 17°51′52″ E) during 2011–2013. The area belongs to the so-called Land of the Great Valleys, where there are deficits in precipitation, extremely unfavorable water balances and increased frequency of long-term periods without precipitation [18,19,21,32–35].

The soil characteristic is presented in Table 1. It was Phaeozem formed from alluvial sand, representing subtype Cambic Phaeozem. The soil showed very low capacity for soil water retention. The content of water available to plants amounted 54 mm, including easily available water 32 mm.

Table 1. Physical properties of the soil according to Rolbiecki et al. [25].

Genetic Horizon	Depth (cm)	Texture	Specific Density ($Mg\ ha^{-1}$)	Bulk Density: Temporary ($Mg\ ha^{-1}$)	Bulk Density: Actual ($Mg\ ha^{-1}$)	Porosity (% vol.)	Moisture (% vol.)
Ap	0–33	slightly loamy sand	2.290	1.426	1.324	42.2	10.02
AC	33–60	loose sand	2.680	1.620	1.591	40.6	2.90
C	60–150	loose sand	2.740	1.691	1.653	39.7	3.80

2.2. Experimental Design

The cultivation of potato (*Solanum tuberosum* L.) mid-early cultivar Courage was managed according to standard crop management practices as recommended for potato under Polish conditions. In the presented research, drip irrigation and nitrogen fertilization by drip fertigation was performed. An experiment was set up using the split-plot system with four replications. Two factors were used in the study. The first order factor was made up of drip irrigation applied at two treatments: O = control (without irrigation), D = drip irrigation. The second order factor was made up by the method of nitrogen fertilization applied at two treatments: P = nitrogen fertilization by broadcasting, F = nitrogen fertilization by drip fertigation.

The area of a single plot for harvest was 11.25 m^2 (1.5 m × 7.5 m). The distance between the rows of plants was 75 cm and the distance between plants in the rows was 30 cm. Nitrogen fertilization dosage was the same for all the experimental treatments and it was 120 kg N ha^{-1}. The nitrogen fertilizer (ammonium nitrate: N-NH_4—17.2% and N-NO_3—17.2%) was supplied at three single intervals, each 40 kg N ha^{-1}: first rate by broadcasting in all the plots (prior to emergence), and second (at the end of June) and third rate (in mid-July) by broadcasting on plots P or by drip fertigation on plots F. In the experiment, nitrogen fertilization was used, i.e., nitrogen feeding in liquid form using an irrigation network and proportional mixing feeders. The phosphorus-potassium fertilization applied in the spring, before the cultivation began, was the same for the entire experiment and it was 100 kg P ha^{-1}, and 150 kg K ha^{-1}. Potato was grown using the full rate (30 t ha^{-1}) of farmyard manure introduced into soil in autumn.

Surface drip irrigation was performed using 'T-Tape' linear drip, with 20 cm between the emitters and the flow rate was 5 l m^{-1} h^{-1}. Irrigation procedure followed the indications of tensiometers (Soil Moisture Equipment Corp, Santa Barbara, CA, USA), not allowing for a decrease in the soil matric potential below −30 kPa [27]. Tensiometers were used to mark the beginning of a single irrigation treatments. At the same time, the water needs of potatoes were estimated using the Hargreaves climate model, which allowed for the estimation of cumulative water consumption of potato. A single tensiometer was installed on each plot, the tensiometer filter was placed at a depth of 25 cm. During irrigation, the soil layer moisture was regulated to 30 cm. Soil wetting in drip irrigation was about 50% of the distance between the rows.

2.3. Weather Conditions

The average temperatures in Kruszyn Krajeński during the growing season (April–September) of potato cultivar Courage in the period of 2011–2013 are presented in Table 2. The mean air temperature in the research years was 14.7 °C, which was 0.1 °C higher compared to the mean for a long-term period (1986–2015). With the mean temperature of 15.2 °C, the growing season 2011 was the warmest. The warmest month of the growing period, in general, was July, which was characterized by the mean temperature of 18.4 °C (0.4 °C below the mean for a long-term period). It should be added that the mean rainfall for the vegetation period (April-September) during the WMO reference period (1981–2010) amounted to 308 mm, and the mean value of air temperature was 14.5 °C.

Table 2. Air temperature (°C) during the growing periods of 'Courage' potato (2011–2013).

Years	Months of Growing Period						Mean
	April	May	June	July	August	September	
2011	10.5	13.4	17.7	17.6	17.7	14.3	15.2
2012	8.4	14.5	15.2	18.8	17.6	13.3	14.6
2013	7.0	14.2	17.4	18.9	18.1	10.7	14.4
Mean for 2011–2013	8.6	14.0	16.8	18.4	17.8	12.8	14.7
Mean for long-term period 1986–2015	8.1	13.3	16.3	18.8	18.0	13.1	14.6

In 2011–2013, the average precipitation in the period from 1 April to 30 September was 322.2 mm, which was 11.6 mm higher than the mean amount for a long-term period (Table 3). The highest precipitation of 378.2 mm occurred during the growing period in 2012 and was 378.2 mm (67.6 mm above the mean for a long-term period). The lowest total rainfall amounted to 234 mm (76.6 mm below the mean for a long-term period), which occurred during growing period in 2011. In June and July, the mean rainfall for 2011–2013 was higher than the mean for a long-term period. The highest monthly rainfall amount was noted in July 2011 (137 mm), June 2012 (133.8 mm), and August 2012 (115.6 mm).

Table 3. Rainfall (mm) data during the growing periods of 'Courage' potato (2011–2013).

Years	Months of Growing Period						Mean
	April	May	June	July	August	September	
2011	0.0	2.0	40.0	137.0	30.7	24.3	234.0
2012	26.5	25.4	133.8	115.6	51.8	25.1	378.2
2013	13.6	91.7	49.3	79.0	56.6	64.1	354.3
Mean for 2011–2013	13.4	39.7	74.4	110.5	46.4	37.8	322.2
Mean for long-term period 1986–2015	26.9	50.2	54.9	71.4	59.7	47.5	310.6

Figures 1–3 show graphically the meteorological conditions in 2010–2013 in the form of Walter climatic diagrams [36]. The curves were made from total precipitation and mean temperatures for the 10-day periods (decades) precisely described in Walter's methodology. Weather conditions showed a high variation in respective growing periods. Dry periods, when the climatodiagram precipitation curve is found below the temperature curve, occurred, in fact, for each month of the irrigation period (June–August), each year.

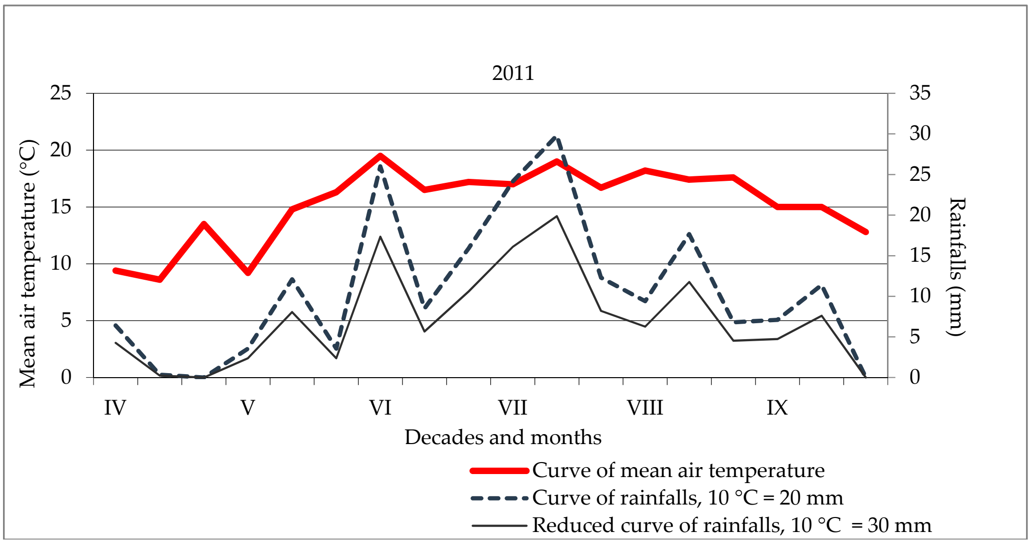

Figure 1. Climatic diagram for meteorological conditions from April to September (IV–IX) in 2011.

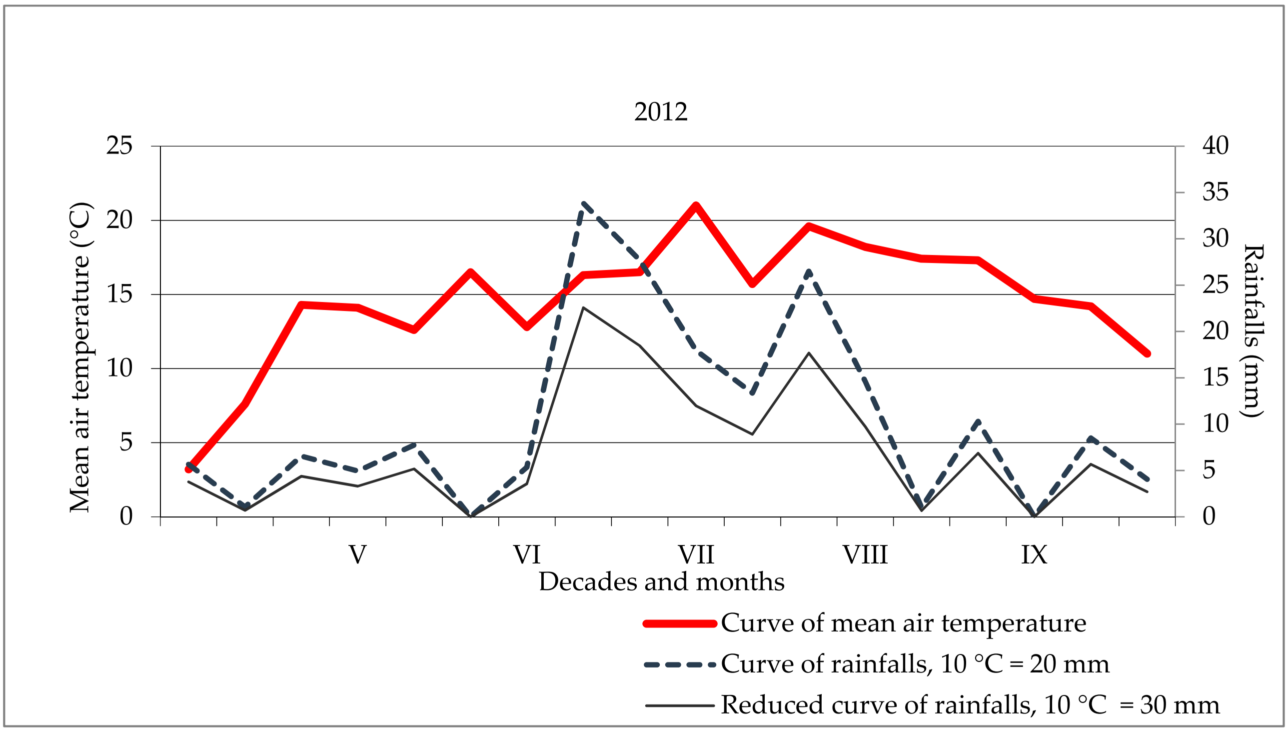

Figure 2. Climatic diagram for meteorological conditions from April to September (IV–IX) in 2012.

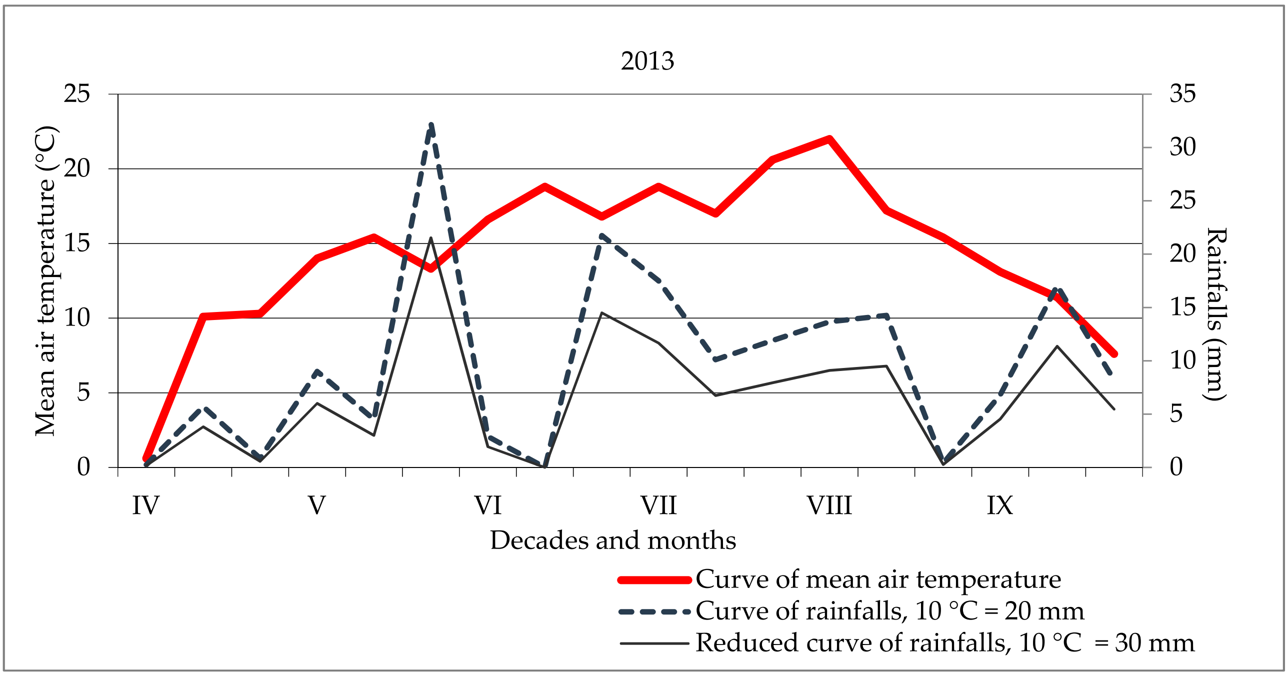

Figure 3. Climatic diagram for meteorological conditions from April to September (IV–IX) in 2013.

2.4. Water Requirements Estimation

Reference evapotranspiration was determined using the Hargreaves model modified by Droogers and Allen, i.e., Hargreaves^{DA} [37]. This model, based on the measurement of the minimum and maximum daily air temperature, was used to calculate the reference evapotranspiration value, because it can be widely used in agricultural practice to determine the water needs of plants and to control irrigation. Its usefulness for calculating reference evapotranspiration in Polish conditions was also confirmed by Treder, et al. [31], Rolbiecki, et al. [38], and Figas, et al. [39].

Crop evapotranspiration of the mid-early potato cultivar Courage was calculated based on the climatic criterion by using crop coefficients (kc), as well as correction coefficients (kr), assumed based on the use of the area by the plants, according to Freeman and Garzoli reported by Rolbiecki, et al. [29]. The kc were determined for the tested plant for the months from June to August, i.e., in the period of tuber formation, i.e., the time of the highest water needs of potatoes. Values of kc for months of irrigation period were the following: 0.4 for June and 0.6 for July and August.

Correction coefficients (kr) according to Freeman and Garzoli for the subsequent decades of the irrigation period determined on the basis of observations of potato plants and measurements carried out in the subsequent growing seasons in the current experiment are presented in Table 4. The data show that the value of the kr increases in subsequent decades of potato growing with the increase in the degree of overgrowing of the area [29].

Table 4. Correction coefficients (kr) according to Freeman and Garzoli for decades and months of the irrigation period, to computing crop evapotranspiration for potato cultivar Courage in central Poland, at the limited wetting area (drip irrigation) ([29] modified by authors).

Decades	Months of Irrigation Period		
	June	July	August
I	0.57	0.9	1.0
II	0.80	1.0	1.0
III	0.85	1.0	1.0

The following were assessed as production effects of drip irrigation: the marketable tuber yield (t ha^{-1}), fresh tuber weight (g), number of tubers per plant (pcs), irrigation water use efficiency (IWUE) and nitrogen use efficiency (NUE) on the nitrogen feeding form. IWUE determines the yield increase due to irrigation in relation to the volume of irrigation water given to the plant during the whole growing period. The indicator shows the unitary production effectiveness of irrigation water [40].

2.5. Statistical Analysis

The results of the marketable tuber yield amount, tuber weight, number of tubers per plant were statistically analyzed. The calculations were provided using computer package ANALWAR-5.FR, by Fisher-Snedecor test to determine the significance of tested factor. The significant differences for examined traits were calculated using the Tukey test at the significance level of $p = 0.05$.

Pearson's linear correlation analysis was performed to find relationships between the studied features. For this purpose, the statistical package Statistica PL 12 by StatSoft was used [41].

3. Results and Discussion

3.1. Irrigation Needs and Water Requirements of Potato

The mean potato irrigation period for research years 2011–2013 started on 26 June and ended on 15 August and lasted, on average, 51 days (Table 5). The shortest irrigation period (47 days) was noted in 2013, and the longest (56 days) in 2011. During the irrigation period, 8 single doses were used on average. The three-research-year-average seasonal irrigation norm (sum of single rates) was 61.1 mm, falling within, depending on the precipitation pattern, the range from 50.0 mm in 2011 to 76.5 mm in 2013.

Table 5. Characteristics of irrigation periods of potato in particular growing seasons.

Years	Irrigation Period			Irrigation Dose	
	Beginning	End	No. of Days	No. of Single Doses	Seasonal Dose (mm)
2011	28.06.	22.08.	56	8	50.0
2012	3.07.	20.08.	49	7	56.0
2013	17.06.	2.08.	47	10	76.5
Mean	26.06.	15.08.	51	8	61.1

During the irrigation period, the soil matric potential was not allowed to drop below −30 kPa. Due to this potential, optimal soil moisture was maintained. According to Nowacki [8], when irrigating potatoes, one must not allow too large fluctuations in soil moisture. Optimal soil moisture, which was from 65% to 70% of the field water capacity, increases the use of nutrients by plants and ensures for the proper development of the root system and the above-ground part (haulm).

In the study reported by Rolbiecki, et al. [29] carried out in 2008–2010 on the same research facility in Kruszyn Krajeński but with other mid-early potato cultivars Vineta and Oman, they applied the seasonal irrigation standard average for three years of 83 mm, depending on the rainfall distribution from 66.5 mm in 2008 to 101 mm in 2010. On the other hand, in experiments with medium-early cultivar potato irrigation [18] conducted at the same facility in 2005–2007, the seasonal irrigation doses ranged from 40 mm in 2007 to 170 mm in 2005 (depending on the distribution of precipitation), and the average for the three seasons was 120 mm. The low standard of irrigation in 2007 resulted mainly from the large amount and even distribution of precipitation.

Some regions of Poland are characterized by a chronic rainfall deficit [42]. In Poland, the highest precipitation deficit for early cultivars occurs in the central part of the country, where this experiment was conducted. The amounts of water used for drip irrigation of potatoes in the present research correspond well with Nowak [43] synthesis, which states that in dry years this deficit ranges from 105 mm to 120 mm.

The analysis of the cumulative decade-long water needs with the drip system of potato cultivar Courage (Figure 4) shows that the values of these water needs were determined directly according to Hargreaves^{DA}'s formulas was 202 mm, ranging over the research years from 189 mm in 2011 to 229 mm in 2013 from 1 June to 31 August.

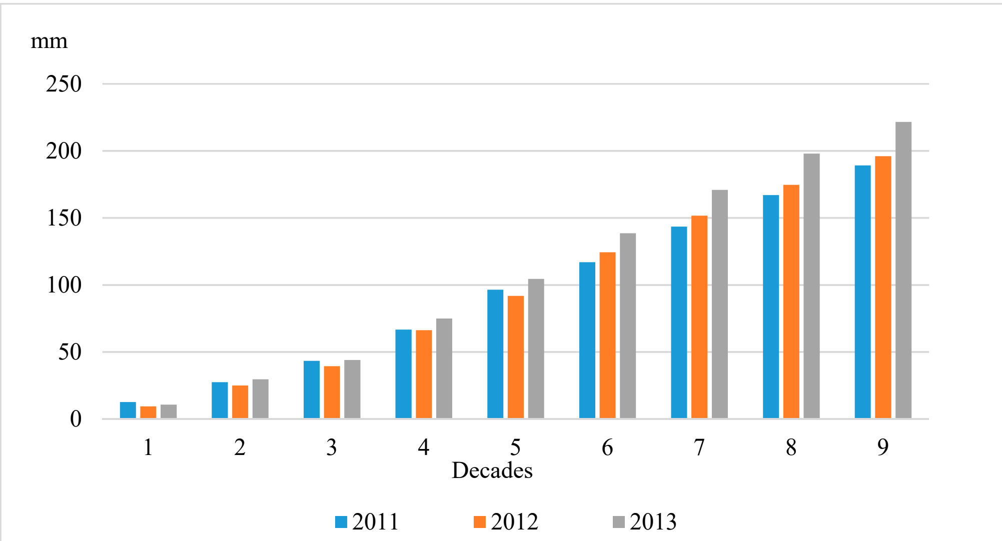

Figure 4. Cumulative water consumption (mm) of potato cultivar Courage determined directly according to Hargreaves^{DA}'s formulas for 9 decades of the period (June–August) in 2011–2013.

3.2. Potato Yielding

On average for the research period, drip irrigation compared with the control, significantly increased the marketable yield of potato tubers from 22.61 t ha^{-1} (O) to 38.53 t ha^{-1} (D); the yield increase being 15.92 t ha^{-1} (55%) (Table 6). The greatest yield increase (20.88 t ha^{-1} namely 89.34%) was due to irrigation in 2012, and the lowest (8.42 t ha^{-1} namely 26.4%) in 2011.

Table 6. Marketable tuber yield (t ha^{-1}) of potato cultivar Courage in 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	Years			Mean
		2011	2012	2013	
Control	Broadcasting	30.73 ^{b}	20.67 ^{b}	11.95 ^{b}	21.11 ^{b}
	Drip fertigation	33.05 ^{a}	26.07 ^{a}	13.20 ^{a}	24.10 ^{a}
Drip irrigation	Broadcasting	38.32 ^{b}	43.70 ^{b}	27.78 ^{b}	36.60 ^{b}
	Drip fertigation	42.31 ^{a}	44.80 ^{a}	34.30 ^{a}	40.47 ^{a}
Influence of irrigation					
Control		31.89 ^{b}	23.37 ^{b}	12.57 ^{b}	22.61 ^{b}
Drip irrigation		40.31 ^{a}	44.25 ^{a}	31.04 ^{a}	38.53 ^{a}
Influence of fertilization					
Broadcasting		34.52 ^{b}	32.18 ^{b}	19.86 ^{b}	28.85 ^{b}
Drip fertigation		37.68 ^{a}	35.43 ^{a}	23.75 ^{a}	32.28 ^{a}
Analysis of variance					
Irrigation (I)		*	*	*	*
Nitrogen fertilization (II)		*	*	*	*
Interaction:					
II/I		ns	*	*	*
I/II		ns	*	*	*

a, b—data with the same letter within a column do not differ significantly at $p < 0.05$ (Tukey test);
*—significant at $p < 0.05$; ns—not significant at $p < 0.05$.

For comparison, in experiments conducted in region of Bydgoszcz with drip irrigation and nitrogen fertigation of the mid-early potato cultivar Vineta, drip irrigation increased the marketable yield of potato tubers from 17.4 t ha^{-1} to 36.3 t ha^{-1} (109%) [29]. In another research, Mazurczyk, et al. [44] with drip irrigation of mid-early potato cultivar Triada carried out also in Poland obtained an increase in tuber yield by 26 t ha^{-1} (88%). In the plots with drip irrigation, farmyard manure and nitrogen fertigation, the yields increased from 29.4 t ha^{-1} to 55.4 t ha^{-1} compared to the control. In other studies, Mazurczyk, et al. [27] drip irrigation and nitrogen fertigation enabled the authors to obtain the yield of the early potato cultivar Owacja to 30 t ha^{-1} on 70th day after planting and about 50 t ha^{-1} after the end of cultivation, i.e., 103rd day after planting. A significant increase in the marketable yield of potato tubers of two potato cultivars (very early 'Monika' and semi-early 'Jolana') in two different regions with reduced rainfall in the Czech Republic during the growing period after the application of drip irrigation has also reported by Elzner, et al. [7].

According to Elzner, et al. [7] and Badr, et al. [28], the increase in the yield of potato tubers depends on specific agri-climatic conditions and ranges from a few percent to multiple increases in yields compared to non-irrigated plots. Nowacki [8] and Głuska [10] report that cultivars with high yielding potential and high water requirements are characterized by a higher yield increment. Due to irrigation, in its development, each potato cultivar has a period of the greatest demand for water, which for potatoes occurs in the phase of tuber setting and the phase of rapid weight gain. This period extends over a period of several weeks, depending on the cultivar, and falls most often from June to the end of August. If there is a shortage of rainfall at that time, the yield increase due to irrigation is the greatest.

Nitrogen fertigation, on average in the years of the study, significantly increased the potato yield from 28.85 t ha^{-1} to 32.28 t ha^{-1} (an increase by 3.43 t ha^{-1}, i.e., 12%). We recorded a significant interaction between drip irrigation and fertigation in developing of the marketable tuber yield. The highest potato yield of the four experimental treatments was noted on plots D + F and on average in the three-year (2011–2013) of the investigated period was 40.47 t ha^{-1}.

A significant impact of the D on the marketable yield of tubers results from the increase of the average weight of tubers (Table 7) and their number (Table 8). Tubers of irrigated plants in the studied period were on average heavier by 22.8 g (37.3%) than those collected from the O plots while the number of tubers per plant increased on average from 8.7 to 14.7.

Table 7. The tuber weight (g) of potato cultivar Courage in 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	Years			Mean
		2011	2012	2013	
Control	Broadcasting	77.9 ^{bc}	56.4 ^{d}	42.7 ^{d}	59.0 ^{c}
	Drip fertigation	62.8 ^{c}	74.6 ^{c}	56.1 ^{c}	64.5 ^{c}
Drip irrigation	Broadcasting	82.0 ^{b}	84.6 ^{b}	75.3 ^{b}	80.6 ^{b}
	Drip fertigation	93.4 ^{a}	90.4 ^{a}	78.1 ^{a}	87.3 ^{a}
Influence of irrigation					
Control		70.4 ^{b}	65.5 ^{b}	49.4 ^{b}	61.2 ^{b}
Drip irrigation		87.7 ^{a}	87.5 ^{a}	76.7 ^{a}	84.0 ^{a}
Influence of fertilization					
Broadcasting		80.0 ^{a}	70.5 ^{b}	59.0 ^{b}	69.8 ^{b}
Drip fertigation		78.1 ^{a}	82.5 ^{a}	67.1 ^{a}	75.9 ^{a}
Analysis of variance					
Irrigation (I)		*	*	*	*
Nitrogen fertilization (II)		ns	*	*	*
Interaction:					
II/I		*	*	*	ns
I/II		*	*	*	ns

$^{a, b, bc, c, d}$—data with the same letter within a column do not differ significantly at $p < 0.05$ (Tukey test); *—significant at $p < 0.05$; ns—not significant at $p < 0.05$.

The results obtained are consistent with Rolbiecki, et al. [29] who reports that drip irrigation has a significant effect on the increase of the weight of tuber and the number of tubers per plant compared to the control (without irrigation). Nagaz, et al. [45] reports that water deficiency during tuber initiation and development has an impact on the decrease in tuber yield, which results from the reduction in the number and weight of tubers. Walworth and Carling [46] also observed a lower number of tubers under non-irrigated conditions.

The second of the examined factors, which is fertigation, also had a significant impact on the weight of tubers and their number. Plants in the D + F treatment were characterized by significantly higher tuber weight compared to the D + P. The tubers of plants collected from the F plots in the studied period were heavier by 6.1 g (8.7%) than those harvested from the treatment P. The number of tubers per plant increased on average from 10.3 to 12.8 after D + F. The largest number of tubers was found in drip irrigated plants, where the D + F was applied. The analysis of the correlation between the tuber yield and the average tuber weight showed a very strong correlation ($r = 0.912$), which indicates that the increase in tuber yield was mainly attributed to the increase in tuber weight (Figure 5).

Table 8. The number of tubers per plant (pcs) of potato cultivar Courage in 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	Years			Mean
		2011	2012	2013	
Control	Broadcasting	7.0 [c]	9.0 [d]	7.0 [c]	7.6 [c]
	Drip fertigation	9.0 [b]	11.0 [c]	8.0 [c]	9.3 [c]
Drip irrigation	Broadcasting	9.0 [b]	18.0 [b]	12.0 [b]	13.0 [b]
	Drip fertigation	15.0 [a]	20.0 [a]	14.0 [a]	16.3 [a]
Influence of irrigation					
Control		8.0 [b]	10.0 [b]	8.0 [b]	8.7 [b]
Drip irrigation		12.0 [a]	19.0 [a]	13.0 [a]	14.7 [a]
Influence of fertilization					
Broadcasting		8.0 [b]	13.5 [b]	9.5 [b]	10.3 [b]
Drip fertigation		12.0 [a]	15.5 [a]	11.0 [a]	12.8 [a]
Analysis of variance					
Irrigation (I)		*	*	*	*
Nitrogen fertilization (II)		*	*	*	*
Interaction:					
II/I		*	ns	ns	ns
I/II		*	ns	ns	ns

[a, b, c, d]—data with the same letter within a column do not differ significantly at $p < 0.05$ (Tukey test); *—significant at $p < 0.05$; ns—not significant at $p < 0.05$.

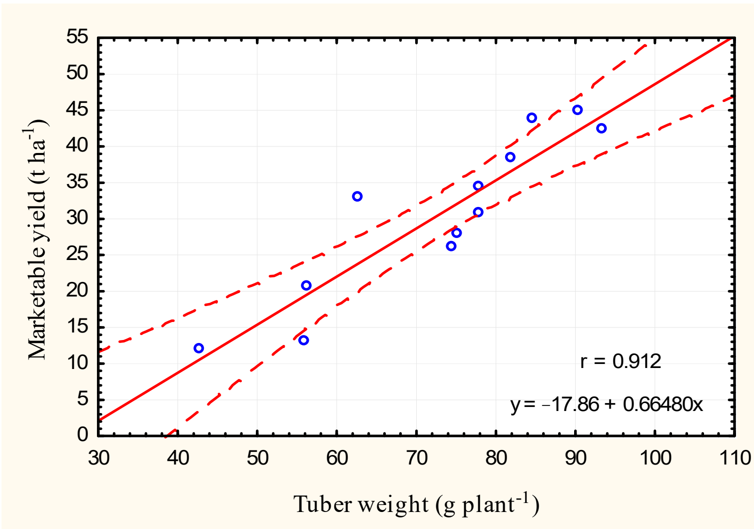

Figure 5. Relationship between marketable yield of tubers and tuber weight per plant of potato cultivar Courage grown under drip irrigation and nitrogen fertilization.

3.3. Irrigation Water Use Efficiency and Nitrogen Use Efficiency

The results of this study show that, on average, for the treatments of D + F and years, it was high and amounted to 260 kg ha^{-1} mm^{-1} (Table 9). In 2011 and 2013, the IWUE index for D + F was higher compared to D + P. This proves that plants in this treatment used water better in conditions of its deficiency or limited amounts in the soil. The heavy rainfall recorded in June and July 2012 was probably the reason for the low IWUE value. According to Nikolaou, et al. [24] pressurized irrigation systems and appropriate irrigation schedules can increase water productivity (i.e., product yield per unit volume of water consumed by the crop) and reduce the evaporative or system loss of water as opposed to traditional surface irrigation methods. A number of other studies also confirm that D + F is an effective method in increasing the efficiency of water use and potato yields [7,12,13,27–30,47]. According to Guoju, et al. [23], improving water efficiency is a key factor for the continued increase in crop productivity in arid and semi-arid regions. D treatments gave higher IWUE compared to other irrigation methods, which results from lower water consumption for drip irrigation [48].

Table 9. Irrigation water use efficiency in the years 2011–2013.

Treatments	Water Use Efficiency (kg ha^{-1} mm^{-1})			
	2011	2012	2013	Mean
Drip irrigation	168	372	241	260
Drip irrigation + fertilization by broadcasting	152	411	207	257
Drip irrigation + fertilization by drip fertigation	185	334	275	264

The NUE, on average for fertilization treatments in the three-year study period (2011–2013), amounted to 189 kg ha^{-1} in O + P and O + F plots and increased to 321 kg ha^{-1} in D + P and D + F plots. Under the conditions of D, this index was 305 kg ha^{-1} in the plots D + P and increased to 337 kg ha^{-1} in the plots D + F (Table 10). The significant impact of irrigation treatments of the potato in the efficiency of nitrogen use under Nubaria region west of Nile Delta of Egypt (arid climate region) is reported by Badr, et al. [28]. The authors obtained the highest value, 176 kg yield kg^{-1} N being in the full drip irrigation treatment ($W_{1.0}$ = 100% of crop evapotranspiration) while the lowest value, 55 kg yield kg^{-1} N in the most severe water deficit treatment ($W_{0.4}$ = 40% of crop evapotranspiration).

Table 10. Nitrogen use efficiency in the years 2011–2013.

Treatments	Nitrogen Use Efficiency (kg ha^{-1} kg N^{-1})			
	2011	2012	2013	Mean
Control + fertilization by broadcasting	256	172	100	176
Control + fertilization by drip fertigation	275	217	110	201
0Mean	266	195	105	189
Drip irrigation + fertilization by broadcasting	319	364	232	305
Drip irrigation + fertilization by drip fertigation	353	373	286	337
Mean	336	369	259	321

4. Conclusions

1. Both the marketable yield and tuber weight, and the number of tubers per plant of 'Courage' potato, increased significantly after using drip irrigation combined with drip fertigation.
2. On the drip irrigated plots with fertilization by drip fertigation, the irrigation water use efficiency increased compared with the drip irrigated plots with fertilization by broadcasting.
3. Compared to the control non-irrigated plots, the nitrogen use efficiency visibly increased on the drip irrigated plots, especially when nitrogen fertilization was applied by drip fertigation.
4. Summarizing, drip irrigation, especially combined with drip fertigation allows us to increase the productivity of the studied mid-early potato cultivar Courage grown on a light soil.

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