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Potato (*Solanum tuberosum* L.) Cultivar Yield and Quality Affected by Irrigation and Fertilization—From Field to Chip Bag

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Abstract: Potatoes are essential for chip production, requiring high quality for processors and high yields for farmers. This two-year study was carried out for the purpose of investigating the influence of irrigation, fertilization, and cultivar on potato yield and tuber and chip quality. Field experiments were conducted in Sombor, Serbia, using a split-split plot design with three replications. Whole-plot treatments involved two irrigation schemes: sprinkler irrigation (SI) used as standard (control) and drip irrigation (DI). Subplot treatments included nitrogen (N) and potassium (K) fertilization in four different combinations: 64 kg N/ha and 64 kg K/ha ($N_{64}K_{64}$) as control; 77 kg N/ha and 110 kg K/ha ($N_{77}K_{110}$); 90 kg N/ha and 156 kg K/ha ($N_{90}K_{156}$); and 103 kg N/ha and 202 kg K/ha ($N_{103}K_{202}$). Sub-subplots comprised three cultivars: VR-808; Pirol; and Brooke. The VR-808 cultivar consistently yielded the highest amount (25.6 and 24.9 t/ha) under both irrigation methods. DI raised tuber flesh temperature compared to SI. The $N_{90}K_{156}$ × Pirol interaction exhibited the highest number of tubers with defects, while $N_{90}K_{156}$ × VR-808 had the fewest. Under DI, the VR-808 cultivar produced chips with the highest total defects, whereas Brooke had the lowest. The postfrying palm oil temperature was the highest for $N_{64}N_{64}$ × Brooke and the lowest for $N_{110}K_{220}$ × Pirol. This study underscores the role of irrigation, fertilization, and cultivar in achieving high yields and high chip quality, providing valuable insights into the whole process, from field to chip bag.

Keywords: irrigation; fertilization; cultivar; potato; tuber; chip

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1. Introduction

Potatoes are a versatile and affordable staple food that plays a significant role in global food security, and their mild flavor and diverse culinary applications make them popular worldwide [1]. In the world, potatoes are cultivated in an area of 16.481.645 ha, achieving an average yield of 22.3 t/ha [2]. With an annual per capita consumption of 32.7 kg [2], a notable portion of this can be attributed to the consumption of potato chips within the total potato consumption.

Potatoes are rich in minerals such as potassium and magnesium, accompanied by phenols and anthocyanins that act as antioxidants [1]. Moreover, potatoes boast an amount of dietary fiber, promoting digestive health and overall wellbeing [1].

Potato chips are one of the most popular snacks, made from thinly sliced potato tubers deep-fried in oil [3,4]. However, to produce high-quality chips, it is essential to cultivate potatoes that meet the rigorous standards of the processing industry. Successful potato production under field conditions necessitates proper irrigation, appropriate fertilization, and the selection of suitable potato cultivars [5].

In standard potato production, irrigation is typically carried out using sprinklers, potentially resulting in significant water losses through dispersion and evaporation [6]. This approach squanders a precious resource and elevates atmospheric moisture levels, creating a suitable environment for potato pathogens such as late blight to proliferate. Moreover, it contributes to increased occurrences of tuber defects, as evidenced by Miller et al. [7]. Consequently, enhancing irrigation by embracing more cost-effective, efficient, and sustainable methodologies is undeniably imperative.

Potatoes meant for chip production have different nitrogen (N) and potassium (K) requirements than those for mashed potatoes or starch production. Potatoes intended for chips are typically fertilized with an emphasis on K, as it decreases the levels of reducing sugars in tubers, resulting in improved chip color [8,9]. Traditional fertilization approaches often involve excessive and unbalanced N and K applications, resulting in low yields and poor tuber quality [8–10]. Moreover, improper fertilization increases tuber susceptibility to defects, impacting chip quality during processing [11–13]. Therefore, research focused on the identification of optimal fertilization practices for potatoes is necessary to improve production and ensure high-quality chips for the market.

In potato chip production, the choice of potato cultivar plays a crucial role [14,15]. Chip cultivars have the potential to produce uniformly sized tubers with a high dry matter content (>20%), as well as tolerance to drought and high temperatures [16,17]. The length of the vegetation period is also essential to ensure a continuous potato harvest in line with logistics, storage, and processing capacities. Considering the vast array of available chip cultivars, there is a need to investigate how these cultivars perform under the conditions of new irrigation and fertilization systems.

Despite the significance of potato chip production as an essential sector in the food industry, there is a notable gap in comprehensive research encompassing the entire process, from the field to a chip bag. While individual studies have delved into specific aspects, such as irrigation [5,18–20], fertilization [21–23], or cultivar selection [14,15,24], few have taken the holistic approach necessary to fully understand how these factors interact throughout the entire potato chip production cycle. Therefore, there is a compelling need for research that bridges this gap by providing a comprehensive insight into how agrotechnical decisions impact the yield and quality of potatoes, from initial cultivation in the field to the final product—chip bags.

This research aims to assess how agrotechnical practices, including irrigation methods, fertilization, and potato cultivars, impact the yield and quality of potato chips. It comprehensively analyzes the entire production process, from field cultivation to the final chip product, to understand the interplay of these factors and their effects on chip quality. Ultimately, the study seeks to improve production practices, promote sustainability and efficient production methods that benefit producers and consumers, and contribute to resource conservation in farmer practices and the potato chip industry.

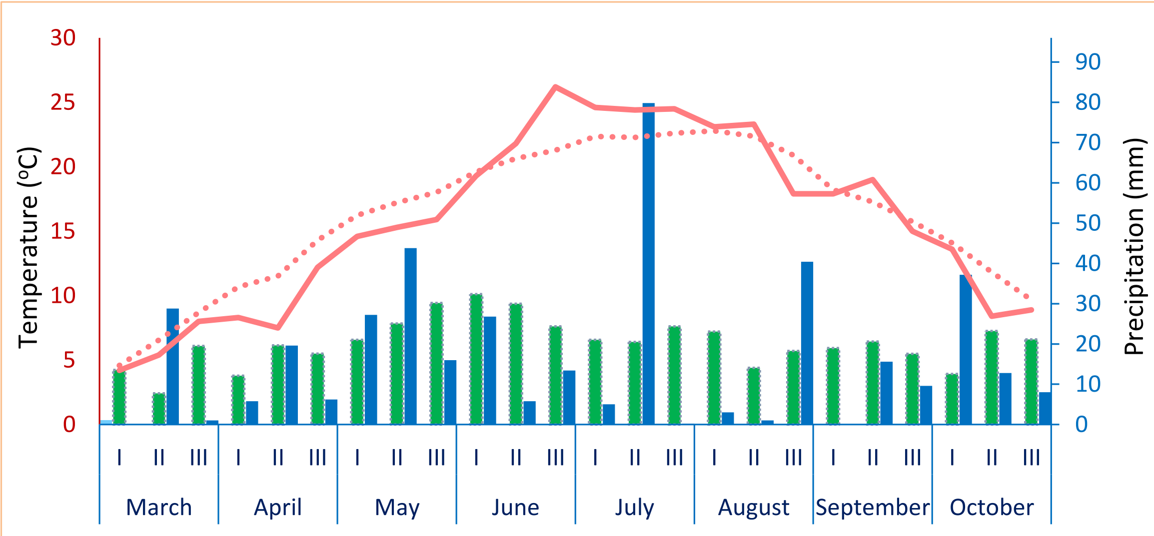
2. Materials and Methods

2.1. Experimental Site

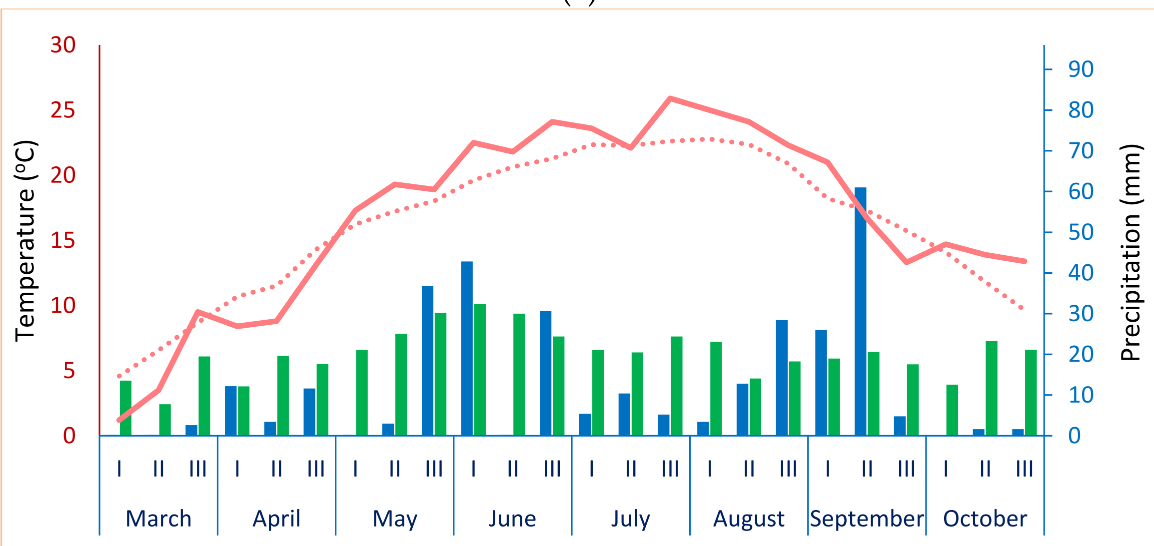
The experiment was conducted in 2021 and 2022 in the experimental fields of the Agricultural Extension Service in Sombor (47° 75′ 33″ N and 19° 13′ 52″ E), located in the Province of Vojvodina, Serbia. Table 1 displays the results of an agrochemical soil analysis from the site where the experiment was conducted over two years, while Figure 1 illustrates the meteorological conditions.

Table 1. Agrochemical analysis of the soil at the experiment site.

Year	Depth (m)	pH	$CaCO_3$	Humus	N	P_2O_5	K_2O
		H_2O	(%)	(%)	(%)	mg 100 g^{-1}	
2021	0.3	7.67	10.39	4.2	0.26	18.0	24.75
2022		7.58	9.52	4.4	0.20	17.90	28.40



(**a**)



(**b**)

Figure 1. Meteorological conditions during potato vegetation in 2021 (**a**) and 2022 (**b**). Precipitation (P)—blue bars; multiyear average P—green bars; temperature (T)—solid red line; multiyear average T—dashed red line.

Based on the pH values, the soil exhibited alkaline characteristics in both years (Table 1). In terms of humus content, the soil was humic with a moderate nitrogen supply. Phosphorus remained within optimal levels during both years, while potassium content was optimal in 2021 but high in 2022 (Table 1). To assess the basic agrochemical indicators, established methods employed in previous potato experiments by Ilin et al. [8] were utilized.

The average air temperature during the study period exhibited notable variations. In the first year, the highest average air temperature occurred in the third decade of June, surpassing the multiyear average by 4.9 °C (Figure 1). Conversely, in the following year, the peak average temperature was observed in the third decade of July, exceeding the multiyear average by 3.3 °C. In terms of precipitation, 2021 experienced the highest rainfall in the second decade of July, exceeding the multiyear average by 59.3 mm (Figure 1). In contrast, 2022 recorded the most significant precipitation in the second decade of September, surpassing the multiyear average by 40.6 mm. The monitoring of meteorological parameters was conducted using an automatic weather station (Vantage Pro2^{TM}) positioned near the experimental plot.

2.2. Experimental Design and Applied Agronomy Practices

The experiment was set up with a split-split plot design with three replications and randomized treatments within each replication.

Whole-plot treatments involved two irrigation schemes: sprinkler irrigation (SI) used as standard (control) and drip irrigation (DI). Subplot treatments included nitrogen (N) and potassium (K) fertilization in 4 different combinations: 64 kg N/ha and 64 kg K/ha ($N_{64}K_{64}$) as control; 77 kg N/ha and 110 kg K/ha ($N_{77}K_{110}$); 90 kg N/ha and 156 kg K/ha ($N_{90}K_{156}$); and 103 kg N/ha and 202 kg K/ha ($N_{103}K_{202}$). Sub-subplots comprised three cultivars: VR-808; Pirol; and Brooke. The size of an experimental sub-subplot was 7.5 m^2 (5×1.5 m).

In the autumn, a standard practice for potato fertilization was conducted that involved applying a complex NPK fertilizer (16:16:16) at a rate of 400 kg/ha, providing 64 kg/ha of nitrogen (N) and potassium (K). Following that, plowing was conducted to a depth of 30 cm. Depending on the treatment of fertilization, KNO_3 (13:0:46) equivalent to 0, 13, 26, or 39 kg N/ha and 0, 46, 92, or 138 kg K/ha was applied in five equal doses (split applications). The first dose was applied before planting, and the remaining doses were administered during the emergence, intensive growth, flowering, and postflowering stages.

In 2021, each irrigation treatment provided 530 mm, whereas in 2022, the sprinkler irrigation system administered 347 mm of water, while the drip irrigation system supplied 381 mm. The irrigation timing was determined based on meticulously monitored soil moisture levels throughout the experiment. Soil moisture monitoring was facilitated utilizing an SKU-6440 sensor, which operated Davis Instruments [25] technology and was strategically positioned at the Vantage Pro2^{TM} meteorological station. This precise monitoring approach was pivotal in optimizing irrigation practices, ensuring the efficient use of water resources. During the potato vegetation stage, weed, disease, and pest control measures were carried out according to the guidelines provided by the plant protection sector of the Extension Service of Sombor [26]. During the vegetation period of the potatoes, we applied an herbicide containing S-metolachlor, a fungicide containing mancozeb, and an insecticide based on acetamiprid.

The potato harvest in 2021 took place on September 28th, while in 2022, it was conducted on October 10th. The differing harvest times were attributed to a substantial rainfall occurrence in the second decade of September during the second year, preventing the potato harvest from taking place (Figure 1). After removing the border rows, yield determination was performed via measuring all plants within the plots. Forty tubers were randomly selected from each plot for quality assessment on the same day. Until the analysis, the tubers were stored at a temperature of 8 °C and a relative air humidity of 95% [27].

2.3. Determination of Tuber and Chip Quality Indicators

The quality analysis of tubers and chips was conducted in a local potato-processing company. This strategic partnership was deliberately chosen to ensure the practical relevance of our research within the food-processing industry. It allowed us to establish a direct connection with real-world chip production conditions, enhancing the applicability of our findings.

2.3.1. Specific Gravity

Specific gravity was determined according to the guidelines outlined by Kleinkopf et al. [28] and calculated using the formula proposed by Islam et al. [29]:

$$\text{Specific gravity} = \frac{\text{Weight of tuber in air}}{\text{Weight of tuber in air} - \text{Weight of tuber in water}}$$

2.3.2. Dry Matter Content

Dry matter content was determined using the gravimetric method described in the Regulation on Food Analysis [30].

2.3.3. Temperature Measurement

The temperature of the tuber flesh and the oil temperature after frying the chips were measured using a digital thermometer with a probe [31].

2.3.4. Determination of Tuber Defects

External tuber defects assessed in this study included green spots, late blight, deformations, secondary growth, bruises, and dry rot. Internal defects consisted of damage caused by pests. These defects were evaluated following established standards commonly used for detecting issues in potatoes intended for chip production [32,33].

2.3.5. Frying and Evaluation of Chip Quality

Potatoes were precisely sliced into 1.25 mm thick slices and subsequently fried in deep palm oil for 3 min at approximately 160 °C. After frying, the chips were placed on filter paper to allow excess oil to drain. Subsequently, a thorough examination was conducted to identify the presence of green spots, undesirable coloration, and edge and nonedge defects of chips [12,34]. This assessment was carried out strictly to industry standards governing chip quality.

2.4. Statistical Analysis

To assess the impacts of irrigation, fertilization, and cultivar on potato yield and the quality of tubers and chips, a factorial analysis of variance (ANOVA) was conducted. The significance of differences was determined using the LSD test at $p < 0.05$. Before analysis, data distribution normality was confirmed using the Kruskal–Wallis test. Given the two-year duration of the study and the extensive dataset, this paper presents the two-year average yield and analyzes the quality of tubers and chips. For statistical analyses, Statistica 14 (TIBCO) software [35] was employed.

3. Results

3.1. Yield of Tubers

On average, in 2021 and 2022, irrigation and cultivar influenced the potato tuber yield (Figure 2). In the sprinkler-irrigated plot, the highest tuber yield was observed for the VR-808 cultivar (25.6 t/ha). In contrast, the lowest yield was recorded for the Pirol cultivar (18.0 t/ha), with a significant difference. A similar pattern was observed in the drip-irrigated plot, where the highest yield was measured for the VR-808 cultivar (24.9 t/ha), and the lowest yield was found for the Pirol cultivar (17.3 t/ha), also with a significant difference.

Over two years, fertilization and cultivar had a significant influence on potato yield, as depicted in Figure 3. The highest tuber yield was achieved with $N_{90}K_{156}$ fertilization for the VR-808 cultivar, reaching 28.0 t/ha. In comparison, the lowest yield of 16.1 t/ha was recorded with $N_{103}K_{202}$ fertilization for the Pirol cultivar, and their difference was significant. Compared to the control ($N_{64}K_{64}$), $N_{90}K_{156}$ fertilization significantly increased the tuber yield by 11.1% for the VR-808 cultivar.

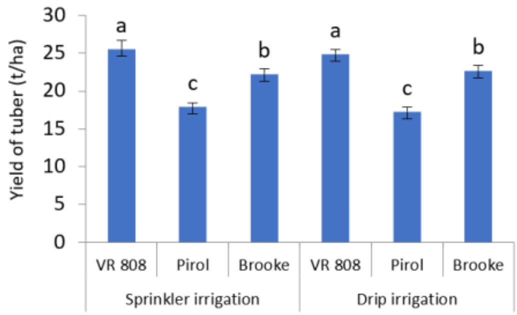


Figure 2. The effects of irrigation and cultivar on potato yield. Lines on bars represent the standard error of the mean (n = 3). Means with different letters are significantly different at $p < 0.05$ according to the LSD test.

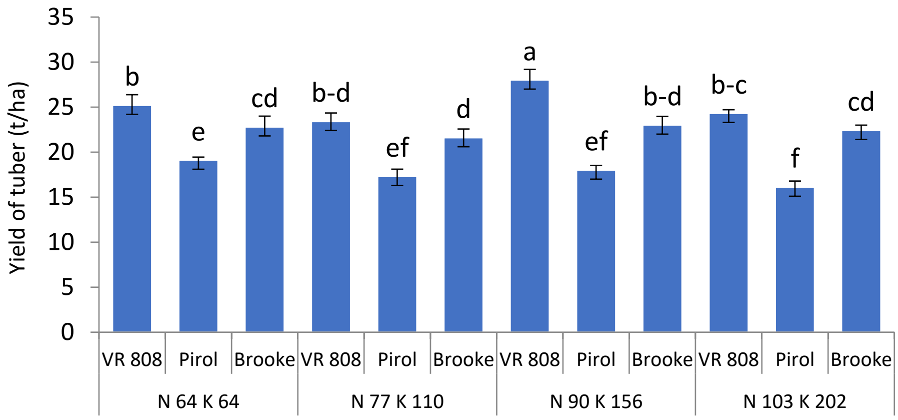


Figure 3. The effects of fertilization and cultivar on potato yield. Lines on bars represent the standard error of the mean (n = 3). Means with different letters are significantly different at $p < 0.05$ according to the LSD test. $N_{64}K_{64}$—64 kg N/ha and 64 kg K/ha; $N_{77}K_{110}$—77 kg N/ha and 110 kg K/ha; $N_{90}K_{156}$—90 kg N/ha and 156 kg K/ha; $N_{103}K_{202}$—103 kg N/ha and 202 kg K/ha.

3.2. Specific Gravity

The average specific gravity of the potatoes was 1.079. Among the cultivars, VR-808 had the highest specific gravity, significantly higher than the other cultivars (Table 2). Under the sprinkler irrigation treatment, VR-808 had the highest specific gravity (1.083), while the lowest was observed in Brooke (1.074), with a significant difference between them. In the drip irrigation plot, the highest specific gravity was recorded for VR-808 (1.087), while Pirol had the lowest (1.071), and their difference was statistically significant.

Table 2. The effects of irrigation and cultivar on the specific gravity of tubers.

Cultivar (C)	Irrigation (I)		Average (C)
	SI (Standard)	DI	
VR 808	1.083 ± 0.00 ab	1.087 ± 0.00 a	1.086 ± 0.00 A
PIROL	1.079 ± 0.00 a–c	1.071 ± 0.00 c	1.075 ± 0.00 B
BROOKE	1.074 ± 0.00 c	1.078 ± 0.00 bc	1.076 ± 0.00 B
Average (I)	1.079 ± 0.00 A	1.079 ± 0.00 A	1.079 ± 0.00

Numbers after ± represent the standard error of the mean (n = 3). Means with different letters in a column are significantly different at $p < 0.05$ according to the LSD test. Capital letters indicate differences among the main effects; lowercase letters indicate differences among interactions. SI—sprinkler irrigation; DI—drip irrigation.

3.3. Dry Matter Content

Irrigation and cultivar significantly influenced the dry matter content in potato tubers (Table 3). The average dry matter content in this study was 20.90%. On average for irrigation, drip-irrigated plots (21.17%) exhibited a significantly higher dry matter content than sprinkler-irrigated plots (20.64%). Among all cultivars, the highest dry matter content was recorded in VR-808 (21.47%), while the lowest was observed in Brooke (20.52%), and the difference between them was significant. On the plot irrigated using sprinklers, the VR-808 cultivar also had the highest dry matter content, while Brooke had the lowest. A similar pattern was observed in plots with drip irrigation, where the VR-808 cultivar had the highest dry matter content, but the Pirol cultivar had the lowest.

Table 3. The effects of irrigation and cultivar on dry matter content.

Cultivar (C)	**Irrigation (I)**		**Average (C)**
	SI (Standard)	**DI**	
VR-808	21.09 ± 0.19 ab	21.85 ± 0.27 a	21.47 ± 0.19 A
PIROL	20.69 ± 0.30 bc	20.77 ± 0.33 bc	20.73 ± 0.21 B
BROOKE	20.17 ± 0.17 c	20.88 ± 0.15 bc	20.52 ± 0.14 B
Average (I)	20.64 ± 0.14 B	21.17 ± 0.17 A	20.90 ± 0.12

Numbers after ± represent the standard error of the mean (n = 3). Means with different letters in a column are significantly different at $p < 0.05$ according to the LSD test. Capital letters indicate differences among the main effects; lowercase letters indicate differences among interactions. SI—sprinkler irrigation; DI—drip irrigation.

3.4. Potato Flesh Temperature

The potato flesh temperature was affected by irrigation and fertilization, as shown in Table 4. Drip irrigation led to a notably higher potato flesh temperature (17.80 °C) than sprinkler irrigation (17.66 °C). Fertilization with $N_{77}K_{110}$ and $N_{103}K_{202}$ resulted in a significantly elevated potato flesh temperature compared to the control ($N_{64}K_{64}$). Among plots with sprinkler irrigation, the highest potato flesh temperature was observed with $N_{77}K_{110}$ fertilization, measuring 17.82 °C. Conversely, the lowest temperature was recorded with $N_{90}K_{156}$ fertilization, reaching 17.52 °C, and the difference between these two temperatures was significant. For the potatoes under drip irrigation, the highest temperature was recorded for $N_{103}K_{202}$ (18.03 °C), significantly higher than the control ($N_{64}K_{64}$), where a temperature of 17.59 °C was measured.

3.5. Defects of Tubers

Irrigation and cultivar significantly impacted the appearance of defects on potato tubers (Table 5). The highest percentage of green patches on tubers was recorded for the VR-808 cultivar under drip irrigation. In contrast, the smallest amount of green patches was observed for the Brooke cultivar under sprinkler irrigation, with a significant difference. The VR-808 cultivar exhibited the highest level of late blight, with sprinkler irrigation increasing late blight compared to drip irrigation. Additionally, the Pirol cultivar subjected to drip irrigation exhibited the most pronounced tuber deformations (2.34%), whereas the Brooke cultivar under sprinkler irrigation showcased the smallest amount of deformations (0.98%). Irrigation had an impact on secondary tuber growth (Table 5). In the interactions, SI × VR-808 exhibited the highest secondary tuber growth (1.02%). Depending on irrigation and cultivar, the highest occurrence of bruises was observed in the SI × Brooke treatment, while there were no bruises in the SI × VR-808 and DI × Brooke treatments. Lastly, concerning dry rot proportions, the VR-808 cultivar under drip irrigation exhibited the highest incidence (13.02%), while the Pirol cultivar under sprinkler irrigation displayed the lowest (4.04%).

Table 4. The effects of irrigation and fertilization on tuber flesh temperature.

Fertilization (F)	Irrigation (I)		Average (F)
	SI (Standard)	DI	
$N_{64}K_{64}$ (control)	17.66 ± 0.08 cd	17.59 ± 0.21 d	17.63 ± 0.11 B
$N_{77}K_{110}$	17.82 ± 0.04 bc	17.93 ± 0.21 ab	17.89 ± 0.10 A
N_{90} K_{156}	17.52 ± 0.07 d	17.65 ± 0.25 cd	17.58 ± 0.12 B
$N_{103}K_{202}$	17.65 ± 0.04 cd	18.03 ± 0.28 a	17.84 ± 0.14 A
Average (I)	17.66 ± 0.03 B	17.80 ± 0.12 A	17.73 ± 0.06

Numbers after ± represent the standard error of the mean (n = 3). Means with different letters in a column are significantly different at $p < 0.05$ according to the LSD test. Capital letters indicate differences among the main effects; lowercase letters indicate differences among interactions. SI—sprinkler irrigation; DI—drip irrigation. $N_{64}K_{64}$—64 kg N/ha and 64 kg K/ha; $N_{77}K_{110}$—77 kg N/ha and 110 kg K/ha; $N_{90}K_{156}$—90 kg N/ha and 156 kg K/ha; $N_{103}K_{202}$—103 kg N/ha and 202 kg K/ha.

Table 5. The effects of irrigation and cultivar on defects of tubers.

Irrigation	Cultivar	Green Patches	Late Blight	Deformations	Secondary Growth	Bruises	Dry Rot
SI (standard)	VR-808	3.06 ± 0.66 a	1.27 ± 0.36 a	1.01 ± 0.62 c	1.02 ± 0.40 a	0.00 ± 0.00 e	6.49 ± 0.55 d
	PIROL	2.83 ± 0.73 a	0.07 ± 0.07 c	1.48 ± 0.50 b	0.00 ± 0.00 c	1.39 ± 0.59 b	4.04 ± 1.01 e
	BROOKE	1.65 ± 0.28 b	1.17 ± 0.60 a	0.98 ± 0.47 c	0.47 ± 0.17 b	2.36 ± 0.89 a	9.65 ± 0.72 b
DI	VR-808	3.36 ± 0.59 a	0.98 ± 0.31 ab	1.58 ± 0.64 b	0.09 ± 0.09 c	0.66 ± 0.43 c	13.02 ± 2.27 a
	PIROL	1.68 ± 0.41 b	0.77 ± 0.51 b	2.34 ± 0.57 a	0.62 ± 0.41 b	0.28 ± 0.19 d	7.89 ± 1.00 c
	BROOKE	2.81 ± 0.72 a	0.23 ± 0.15 c	1.86 ± 0.12 b	0.00 ± 0.00 c	0.00 ± 0.00 e	12.83 ± 0.82 a

Numbers after ± represent the standard error of the mean (n = 3). Means with different letters in a column are significantly different at $p < 0.05$ according to the LSD test. SI—sprinkler irrigation; DI—drip irrigation.

On average for both years, fertilization and cultivar significantly influenced the defects of potato tubers (Table 6). In the case of the VR-808 cultivar fertilized with $N_{103}K_{202}$, the highest occurrence of green patches was determined (4.33%). In comparison, the smallest amount was found in the Pirol cultivar at the same fertilizer dosage (0.32%) with a significant difference. The highest incidence of late blight was recorded in the $N_{77}K_{110}$ × VR-808 interaction (1.97%) and was significantly higher than the control ($N_{64}K_{64}$), where no instances of late blight were detected. The tuber deformations were highest in the VR-808 cultivar with $N_{103}K_{202}$ fertilization (3.92%) and smallest in the same cultivar with $N_{90}K_{156}$ fertilization (0.11%), with a significant difference. The highest secondary tuber growth was noted in $N_{90}K_{156}$ × Pirol, while tubers of the same cultivar under control ($N_{64}N_{64}$) did not exhibit secondary growth. The most bruises were found in tubers grown on plots of $N_{64}K_{64}$ × Brooke (2.27%), whereas no bruises were noted in the same cultivar under fertilization with $N_{90}K_{156}$ and $N_{103}K_{202}$. Fertilization and cultivar had an impact on the occurrence of dry rot in potato tubers (Table 6). The highest dry rot proportion was observed in the $N_{103}K_{202}$ × VR-808 treatment (13.29%), and the smallest was in the $N_{103}K_{202}$ × Pirol treatment (2.27%), with a significant difference.

Table 6. The effects of fertilization and cultivar on defects of the tubers.

Fertilization	Cultivar	Green Patches	Late Blight	Deformations	Secondary Growth	Bruises	Dry Rot
$N_{64}K_{64}$	VR-808	2.51 ± 0.26 de	0.00 ± 0.00 e	1.02 ± 0.59 e	1.01 ± 0.41 a	0.00 ± 0.00 d	6.43 ± 0.86 c
	PIROL	3.93 ± 1.01 bc	0.00 ± 0.00 e	1.41 ± 0.82 e	0.00 ± 0.00 c	0.91 ± 0.53 c	9.53 ± 1.40 b
	BROOKE	1.44 ± 0.23 f	0.12 ± 0.12 e	1.02 ± 0.60 e	0.49 ± 0.28 b	2.27 ± 1.31 a	8.29 ± 0.79 b
$N_{77}K_{110}$	VR-808	4.07 ± 1.09 ab	1.97 ± 0.21 a	0.12 ± 0.12 f	0.00 ± 0.00 c	0.00 ± 0.00 d	9.50 ± 1.15 b
	PIROL	2.84 ± 0.30 cd	0.15 ± 0.15 e	1.16 ± 0.51 e	0.00 ± 0.00 c	0.00 ± 0.00 d	6.57 ± 0.64 c
	BROOKE	1.74 ± 0.52 ef	1.94 ± 1.12 ab	1.19 ± 0.55 e	0.00 ± 0.00 c	2.45 ± 1.42 a	12.26 ± 1.54 a
$N_{90}K_{156}$	VR-808	1.93 ± 0.23 ef	1.45 ± 0.57 bc	0.11 ± 0.11 f	0.00 ± 0.00 c	0.00 ± 0.00 d	9.80 ± 2.85 b
	PIROL	2.40 ± 0.89 de	1.55 ± 0.91 a–c	1.87 ± 1.08 cd	1.24 ± 0.74 a	0.00 ± 0.00 d	5.49 ± 1.17 c
	BROOKE	2.31 ± 0.92 de	0.74 ± 0.25 d	1.11 ± 0.38 e	0.00 ± 0.00 c	0.00 ± 0.00 d	12.03 ± 0.74 a
$N_{103}K_{202}$	VR-808	4.33 ± 1.04 a	1.10 ± 0.19 cd	3.92 ± 0.44 a	1.20 ± 0.72 a	1.32 ± 0.76 b	13.29 ± 4.65 a
	PIROL	0.32 ± 0.20 g	0.00 ± 0.00 e	3.19 ± 0.24 b	0.00 ± 0.00 c	2.45 ± 0.77 a	2.27 ± 1.31 d
	BROOKE	3.48 ± 1.12 bc	0.00 ± 0.00 e	2.37 ± 0.40 c	0.44 ± 0.26 b	0.00 ± 0.00 d	12.39 ± 1.23 a

Numbers after ± represent the standard error of the mean (n = 3). Means with different letters in a column are significantly different at $p < 0.05$ according to the LSD test. $N_{64}K_{64}$—64 kg N/ha and 64 kg K/ha; $N_{77}K_{110}$—77 kg N/ha and 110 kg K/ha; $N_{90}K_{156}$—90 kg N/ha and 156 kg K/ha; $N_{103}K_{202}$—103 kg N/ha and 202 kg K/ha.

Across both years of the study, irrigation and cultivar demonstrated notable effects on potato tuber defects (Figure 4). The Pirol cultivar exhibited the highest level of internal tuber defects (34.23%), while the VR-808 cultivar showcased the lowest (12.96%) in plots with sprinkler irrigation, with a significant difference between them. The most pronounced external defects were found in the VR-808 cultivar under drip irrigation, whereas the fewest defects occurred in the Pirol cultivar (9.83%) irrigated with sprinklers. Total tuber defects were the most present in the Pirol cultivar and the least in the VR-808 cultivar under the sprinkler treatment, with a significant difference. Fertilization and cultivar also influenced tuber defects (Figure 5). The highest amount of internal tuber defects was observed in the Pirol cultivar on plots fertilized with $N_{90}K_{156}$ (38.61%), while the lowest was in the VR-808 cultivar (8.03%) at the same fertilization dosage. Regarding external defects, the VR-808 cultivar had the highest percentage (25.18%), while the Pirol cultivar (8.25%) displayed the lowest under $N_{103}K_{202}$ fertilization. The highest amount of total defects was recorded in $N_{90}K_{156}$ × Pirol (51.18%), while the treatment of $N_{90}K1_{56}$ × VR-808 had the fewest total defects.

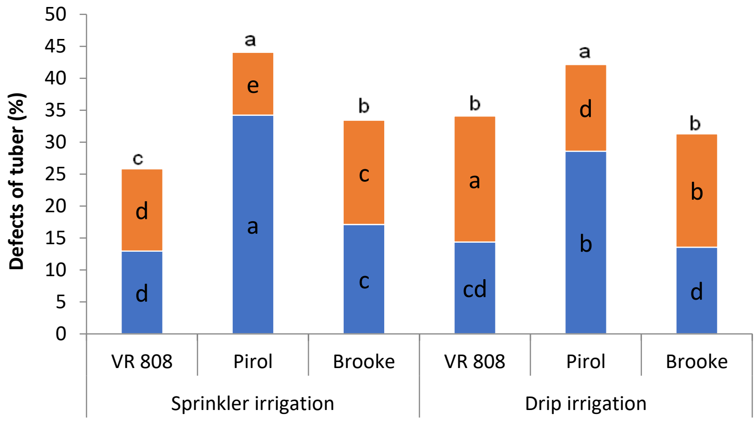


Figure 4. The effects of irrigation and cultivar on tuber defects. Blue bars—internal defects of tubers; orange bars—external defects of tubers; blue + orange bars—total defects of tubers. Means (n = 3) with different letters are significantly different at $p < 0.05$ according to the LSD test.

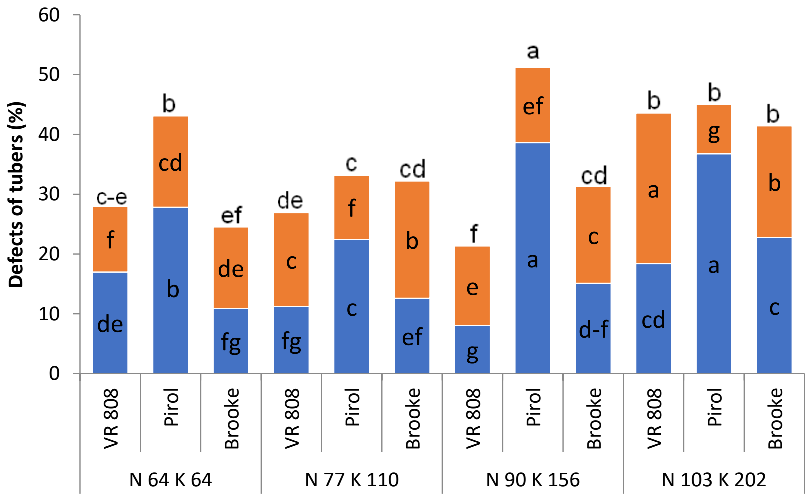


Figure 5. The effects of fertilization and cultivar on tuber defects. Blue bars—internal defects of tubers; orange bars—external defects of tubers; blue + orange bars—total defects of tubers. Means (n = 3) with different letters are significantly different at $p < 0.05$ according to the LSD test. $N_{64}K_{64}$—64 kg N/ha and 64 kg K/ha; $N_{77}K_{110}$—77 kg N/ha and 110 kg K/ha; $N_{90}K_{156}$—90 kg N/ha and 156 kg K/ha; $N_{103}K_{202}$—103 kg N/ha and 202 kg K/ha.

3.6. Indicators of Chip Defects

The irrigation and cultivar factors played a significant role in the occurrence of chip defects (Table 7). The highest percentage of green patches was observed in chips from the DI × VR-808 interaction (2.81%), whereas the lowest was noted in DI × Pirol (0.64%), with a significant difference between them. The chips with the most undesirable coloration (2.97%) were produced from tubers originating from the SI × Brooke treatment, whereas the lowest percentage (0.53%) occurred in the SI × Pirol treatment. Interestingly, sprinkler irrigation reduced the prevalence of nonedge defects in chips made from the VR-808 and Pirol cultivars compared to those produced using drip irrigation. The chips originating from DI × Pirol tubers displayed the most nonedge defects (19.44%), whereas the chips from DI × Brooke tubers had the fewest (3.27%). Edge defects of chips were most prominent in chips fried from DI × Brooke tubers (17.98%), while the smallest amount was in chips from SI × Pirol (14.02%), with a significant difference between them. Irrigation and cultivar also influenced the postfrying oil temperature changes (Table 7). The highest palm oil temperature after frying was observed in chips from SI × VR-808 (156.39 °C), significantly higher than the postfrying oil temperature of DI × VR-808 (155.50 °C).

Table 7. The effects of irrigation and cultivar on chip defects (%).

Irrigation	Cultivar	Green Patches	Undesirable Coloration	Nonedge Defects	Edge Defects	Temperature after Frying
SI (standard)	VR-808	1.76 ± 0.24 b	1.14 ± 0.50 b	11.24 ± 0.85 c	13.07 ± 2.06 cd	156.39 ± 0.20 a
	PIROL	0.77 ± 0.31 d	0.53 ± 0.20 c	15.51 ± 0.58 b	14.02 ± 2.74 bc	155.61 ± 0.23 cd
	BROOKE	0.82 ± 0.21 d	2.97 ± 0.18 a	7.31 ± 0.51 d	14.74 ± 0.60 b	156.20 ± 0.10 ab
DI	VR-808	2.81 ± 0.82 a	0.37 ± 0.26 cd	18.29 ± 3.53 a	17.17 ± 2.09 b	155.50 ± 0.10 d
	PIROL	0.64 ± 0.19 d	0.28 ± 0.14 d	19.44 ± 2.64 a	12.20 ± 0.62 d	155.40 ± 0.22 d
	BROOKE	1.31 ± 0.63 c	0.25 ± 0.10 d	3.27 ± 0.91 e	17.98 ± 1.82 a	155.88 ± 0.25 bc

Numbers after ± represent the standard error of the mean (n = 3). Means with different letters in a column are significantly different at $p < 0.05$ according to the LSD test. SI—sprinkler irrigation; DI—drip irrigation.

On average for 2021 and 2022, fertilization and cultivar influenced chip defects (Table 8). Chips from the $N_{77}K_{110}$ × VR-808 treatment exhibited the highest appearance of green patches (3.29%), while chips made from $N_{77}K_{110}$ × Pirol potatoes had the lowest occurrence of green patches, with a significant difference. Chips produced from the $N_{77}K_{110}$ × Brooke treatment displayed the highest prevalence of undesirable coloration, whereas the $N_{103}K_{202}$ × VR-808 and $N_{103}K_{202}$ × Pirol treatments did not result in such coloring. The highest proportion of nonedge defects was noted in chips originating from $N_{103}K_{202}$ × VR-808 (22.43%), while chips of the same cultivar under the control treatment ($N_{64}K_{64}$) displayed significantly lower levels of nonedge defects (14.66%). Chips from the $N_{103}K_{202}$ × VR-808 treatment showcased the highest incidence of edge defects (22.50%), in contrast to the $N_{77}K_{110}$ × Pirol interaction, which had the lowest occurrence (6.37%), with a significant difference between them. Additionally, fertilization and cultivar affected oil temperatures after frying (Table 8). The highest oil temperature after frying was observed in chips from the $N_{64}K_{64}$ × Brooke treatment (156.43 °C), while the lowest was noted after frying chips from $N_{110}K_{202}$ × Pirol (155.00 °C), demonstrating a significant difference between them.

Throughout the two-year study period, irrigation and cultivar significantly impacted the total chip defect results (Figure 6). On plots irrigated with sprinklers, the highest amount of chip total defects was recorded for Pirol (30.84%), while the lowest was observed for Brooke (25.85%), and their difference held statistical significance. Conversely, chips with the highest total defects were produced from the VR-808 cultivar on plots irrigated using drip irrigation, whereas the lowest amount of total defects was associated with Brooke. Fertilization practices and cultivars also had a distinct effect on the extent of chip defects (Figure 7). Potato chips derived from the VR-808 cultivar and treated with $N_{103}K_{202}$ fertilizer displayed the highest total defects. Conversely, for the Brooke cultivar treated with $N_{64}K_{64}$, the total defect rate was notably lower, showing a significant difference.

Table 8. The effects of fertilization and cultivar on chip defects (%).

Fertilization	Cultivar	Green Patches	Undesirable Coloration	Nonedge Defects	Edge Defects	Temperature after Frying
$N_{64}K_{64}$	VR-808	3.21 ± 0.75 ab	0.74 ± 0.47 c	14.66 ± 1.59 c	14.41 ± 1.36 de	155.93 ± 0.25 a–c
	PIROL	1.73 ± 0.22 c	0.26 ± 0.26 de	20.09 ± 3.18 ab	13.46 ± 0.47 e	155.88 ± 0.19 bc
	BROOKE	0.31 ± 0.18 d	1.20 ± 0.69 b	6.03 ± 0.47 e	14.31 ± 0.80 de	156.43 ± 0.25 a
$N_{77}K_{110}$	VR-808	3.29 ± 0.19 a	0.66 ± 0.38 c	10.07 ± 1.77 d	14.42 ± 2.89 de	155.96 ± 0.28 a–c
	PIROL	0.30 ± 0.18 d	0.74 ± 0.16 c	18.57 ± 2.63 b	6.37 ± 2.06 g	155.88 ± 0.33 bc
	BROOKE	0.64 ± 0.39 d	1.91 ± 0.86 a	5.52 ± 2.03 d	15.19 ± 0.65 de	155.77 ± 0.39 c–d
$N_{90}K_{156}$	VR-808	1.37 ± 0.05 c	1.61 ± 0.93 a	11.90 ± 2.58 cd	9.17 ± 1.65 f	155.67 ± 0.14 cd
	PIROL	0.39 ± 0.24 d	0.57 ± 0.33 cd	19.10 ± 1.60 b	14.97 ± 0.90 de	155.27 ± 0.30 de
	BROOKE	0.60 ± 0.36 d	1.57 ± 0.56 a	5.68 ± 0.30 d	15.62 ± 1.31 cd	156.08 ± 0.09 a–c
$N_{103}K_{202}$	VR-808	1.28 ± 0.79 c	0.00 ± 0.00 f	22.43 ± 6.04 a	22.50 ± 1.64 a	156.22 ± 0.54 ab
	PIROL	0.39 ± 0.13 d	0.00 ± 0.00 f	12.13 ± 2.60 cd	17.65 ± 3.09 c	155.00 ± 0.22 e
	BROOKE	2.72 ± 0.78 b	1.75 ± 1.01 a	3.94 ± 2.29 d	20.33 ± 3.26 b	155.87 ± 0.23 bc

Numbers after ± represent the standard error of the mean (n = 3). Means with different letters in a column are significantly different at $p < 0.05$ according to the LSD test. $N_{64}K_{64}$—64 kg N/ha and 64 kg K/ha; $N_{77}K_{110}$—77 kg N/ha and 110 kg K/ha; $N_{90}K_{156}$—90 kg N/ha and 156 kg K/ha; $N_{103}K_{202}$—103 kg N/ha and 202 kg K/ha.

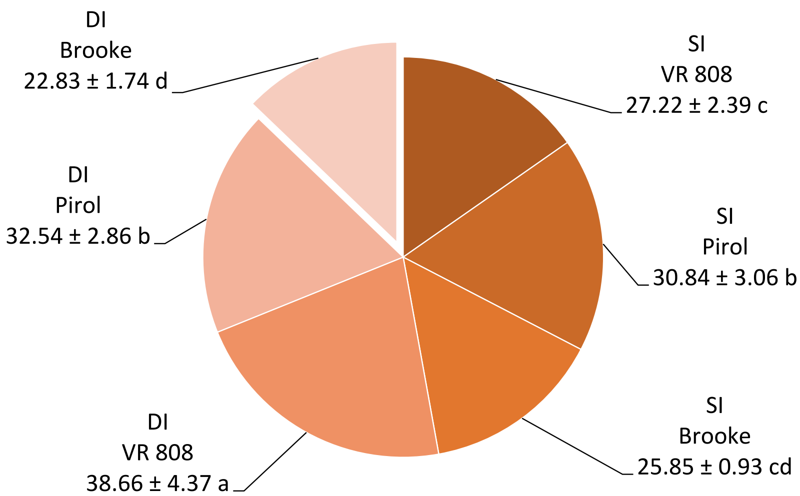


Figure 6. The impacts of irrigation and cultivar on total chip defects. Numbers after ± represent the standard error of the mean (n = 3). Means with different letters are significantly different at $p < 0.05$ according to the LSD test. SI—sprinkler irrigation; DI—drip irrigation. Numbers after ± represent the standard error of the mean (n = 3). Lighter color in the figure corresponds to a higher percentage, while darker color corresponds to a lower percentage.

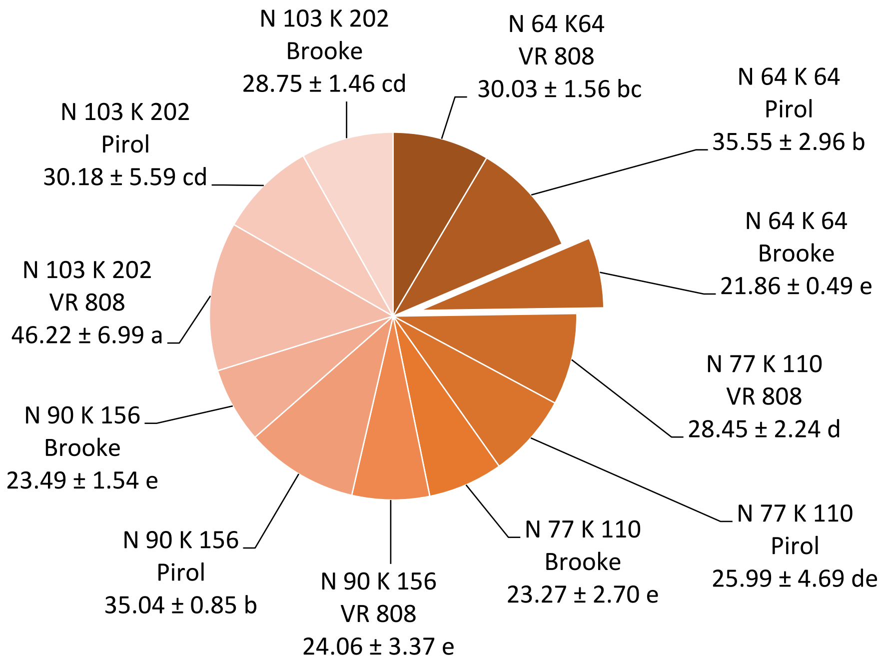


Figure 7. The impacts of fertilization and cultivar on total chip defects. Numbers after ± represent the standard error of the mean (n = 3). Means with different letters are significantly different at $p < 0.05$ according to the LSD test. $N_{64}K_{64}$—64 kg N/ha and 64 kg K/ha; $N_{77}K_{110}$—77 kg N/ha and 110 kg K/ha; $N_{90}K_{156}$—90 kg N/ha and 156 kg K/ha; $N_{103}K_{202}$—103 kg N/ha and 202 kg K/ha. Lighter color in the figure corresponds to a higher percentage, while darker color corresponds to a lower percentage.

4. Discussion

Potato yield and quality are often constrained by water management and the characteristics of cultivars [36,37]. The outcomes of this study underscore the remarkable influence of irrigation methods and cultivars on potato tuber yield. Notably, higher yields were observed in the VR-808 cultivar on SI and DI plots. The consistency in achieving elevated yields can be attributed to the cultivar's inherent genetic traits that equip it with robust growth capabilities [38,39]. These traits may encompass efficient water utilization, nutrient uptake, and adaptability to diverse environmental conditions [6,40,41]. Similar findings were obtained by Ilin et al. [36], who investigated the effects of irrigation on the yield of the Desire potato cultivar meant for mashed potatoes. In this study, applying different N and K fertilizers to various cultivars significantly influenced yield. Notably, the VR-808 cultivar displayed the highest yield when treated with $N_{90}K_{156}$, resulting in a substantial increase compared to the control dosage ($N_{64}K_{64}$). This observation aligns with the findings of Ilin et al. [8] and Misgina et al. [22], who suggest that the optimal K dosage for potatoes is around 150 kg/ha. As an essential macronutrient, K plays a role in various metabolic processes, including water absorption, nutrient transport, and carbohydrate synthesis [13]. Conversely, the Pirol cultivar's lower yields with $N_{103}K_{202}$ fertilizer may indicate an oversupply or imbalance of K relative to its requirements. Excessive K can disrupt nutrient balance, impacting overall nutrient uptake and plant health [5,13].

The results of this study further emphasize the significant influence of potato tuber quality on chip production. The specific gravity of potatoes plays a crucial role in determining the density and texture of potato tubers, directly impacting the quality of the resulting chips [42]. According to Lulai and Orr [43], high specific gravity in potato tubers led to lower oil content in fried chips and higher chip yield. The same authors reported that specific gravity in the range of 1.060 to 1.110 was optimal, which aligns with the findings of this research. Similar results were also reported by Islam et al. [29]. In this study, the VR-808 cultivar consistently displayed the highest specific gravity values across all treatments, indicating characteristics conducive to desirable chip texture. When two ways of irrigation were compared, the VR-808 cultivar displayed higher specific gravity when subjected to drip irrigation, possibly due to more precise water delivery than sprinkler irrigation, which exhibits significant variability in water delivery. This finding is in line with Günel and Karadoğan [18].

The dry matter content significantly influences chips' processing efficiency, color, texture, and crispiness. Achieving over 20% dry matter content for the chip industry is essential [16,17]. In this study, all cultivars had dry matter contents exceeding 20%. However, there was considerable variation among cultivars and irrigation methods. The VR-808 cultivar stood out with the highest dry matter content. This could be attributed to its genetic predisposition for efficient water and nutrient uptake [29]. In a similar study, El-Zohiri and Asfour [24] observed a higher dry matter content in the Lady Palfour cultivar compared to Oceania. Regarding irrigation methods, drip-irrigated plots exhibited higher dry matter content than sprinkler irrigation. This can be explained by the better water delivery by the drip system, enhancing water and nutrient absorption efficiency in plants [18,44].

Measuring the temperature of potato flesh before frying is essential for adjusting the temperature during the frying process. This ensures the chips are cooked to the desired crispiness without undesirable coloration or taste [45,46]. Additionally, monitoring the temperature of the flesh can also indicate potential diseases or issues during storage, highlighting the need for permanent monitoring to uphold overall product quality. In this study, the temperature of the potato flesh remained within the standard range (17–19 °C), indicating suitable conditions for chip production.

Torabian et al. [13] emphasized that external factors, such as tuber size, shape, skin and flesh color, greening, and mechanical damage, contributed to the overall assessment of potato tuber quality for chip production. Porter et al. [47] found that reduced irrigation led to increased external tuber defects. In this study, irrigation and cultivar properties significantly influenced the occurrence of tuber defects. Miller et al. [7] found that the characteristics of different potato cultivars significantly impacted tuber damage, suggesting variable levels of susceptibility among different cultivars, which is in line with the results of this research. These findings underscore the importance of careful cultivar selection and the implementation of an appropriate irrigation system to achieve high-quality potatoes for chip production.

Within the realm of external defects, it is noteworthy that the VR-808 cultivar, when fertilized with $N_{103}K_{202}$, exhibited significantly more green patches than the Pirol cultivar at the same fertilizer dosage. This is in accordance with the findings of Braun et al. [48], who identified a correlation between increasing nitrogen dose and the prevalence of green patches on potato tubers. Furthermore, the VR-808 cultivar demonstrated heightened susceptibility to late blight, particularly when subjected to sprinkler irrigation. This susceptibility could be attributed to differences in moisture retention and leaf humidity [49,50]. Regarding fertilization, it is noteworthy that the VR-808 cultivar, when treated with $N_{77}K_{110}$, exhibited a significant increase in late blight compared to the control ($N_{64}K_{64}$).

In contrast, such an effect of $N_{77}K_{110}$ was not observed in the other cultivars. The more pronounced susceptibility of the VR-808 cultivar to late blight due to fertilization could be attributed to its genetic sensitivity. Such an observation may be linked to insufficient supply with K, since Erbet et al. [10] emphasized the vital role of balanced K nutrition in mitigating tuber diseases across different potato genotypes.

The Pirol cultivar exhibited the most pronounced deformities, especially under drip irrigation. These deformities resulted in irregularly sized tubers with significant losses during peeling and cutting [51]. On the other hand, the VR-808 cultivar treated with $N_{103}K_{202}$ displayed the highest incidence of tuber deformations, while the same cultivar treated with $N_{90}K_{156}$ had the fewest deformations. Excessive K fertilization could potentially explain this variation. Similar results were reported by Szpunar-Krok et al. [52] in their study with Sagitta culinary-type potatoes, indicating the significance of K management in tuber deformities. In the case of N, Reiter et al. [53] found that increased N levels led to more tuber deformities, with the Goldrush cultivar showing significantly more deformations than the Norkotash. Furthermore, in this research, a high K dose significantly increased secondary tuber growth in the VR-808 cultivar, likely due to the plant's response to stress conditions caused by K overdosing.

The influence of color on chip quality cannot be overstated, as consumer preferences lean toward golden-yellow chips free of discoloration and frying damage, essential for manufacturers striving to maintain competitiveness.

The highest percentage of green patches was observed in potato chips grown in the DI × VR-808 plot. At the same time, the lowest was recorded for the DI × Pirol interaction, with a significant difference between them. With respect to fertilization, the highest occurrence of green patches was recorded in chips made from $N_{77}K_{110}$ × VR-808 potatoes, while under the same fertilization, the Pirol cultivar exhibited the fewest defects. These findings align with Tanios et al. [54], emphasizing the importance of balanced fertilization in reducing the occurrence of green patches. As highlighted by Islam et al. [29], color is one of the paramount parameters of chip quality. Chips produced from $N_{77}K_{110}$ × Brooke potatoes exhibited the most undesirable color, whereas the highest N and K doses in the VR-808 and Pirol cultivars resulted in the least undesirable coloration. This aligns with the findings of Bélanger et al. [11], who observed that chips had a darkened color when potatoes were fertilized with 100 kg N/ha compared to 200 kg N/ha.

Sandhu et al. [12] emphasized that N fertilization and potato cultivar significantly influenced the color of fried chips. In our study, sprinkler irrigation reduced the presence of nonedge defects in chips made from VR-808 and Pirol cultivars compared to chips produced from potatoes with drip irrigation. Edge defects were more pronounced in chips from the DI × Brooke plot, while the least defects were observed in chips from the SI × Pirol treatment. Temperature after frying is a crucial parameter in controlling chip quality. A lower temperature can lead to chips absorbing more oil, producing poorer quality. In this study, it was observed that, depending on the irrigation method, fertilization, and cultivar, the oil temperature after frying potato samples varied. Nevertheless, across all treatments, the temperature consistently stayed within acceptable limits (<160 °C), thus guaranteeing that chips from each treatment belonged to the highest quality category.

5. Conclusions

Based on two years of research results examining the impact of irrigation, fertilization, and cultivar on potato yield and quality of tubers and chips, the following conclusions can be drawn:

The highest potato yield was achieved by the VR-808 cultivar, which was fertilized with 90 kg N/hs and 156 kg K/ha, with no significant differences observed between the two irrigation methods.

Tuber-specific gravity was solely determined using cultivar and was the highest in the VR-808 cultivar. This underscores the importance of potato cultivars in attaining desired tuber characteristics.

Drip irrigation proved more efficient, significantly increasing dry matter content while reducing tuber defects. This is valuable for sustainable cultivation, as it optimizes water resource use and enhances potato quality.

Observed defects in potato tubers on plots fertilized with 103 kg N/ha and 202 kg K/ha highlight the importance of precise fertilizer management to avoid adverse consequences from excessive K doses.

Chips from Brooke cultivars irrigated with drip irrigation overall had the fewest total defects. This suggests the potential for selecting the optimal interaction between irrigation and cultivars for high-quality chip production.

In conclusion, this study emphasizes the significant impacts of irrigation, fertilization, and cultivar on potato yield and chip quality. Additionally, this study confirms that agronomic limitations cannot be corrected during processing. Finally, these findings hold significance for farmers and the chip industry, offering valuable guidance to optimize production from the field to the chip bag.

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