Role of Potassium in Modifying the Potato Physiological Responses to Irrigation Regimes Under Different Planting Patterns

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Abstract

The evaluation of potato's responses to potassium fertilizer and planting pattern under water shortage condition may help identify the factors affecting plant resistance to water deficit. In this regard, an experiment was conducted with three replications aiming to explore the effects of different levels of irrigation (60, 80 and 100% of crop water requirement) and potassium sulphate fertilizer (0, 75 and 150 kg K_2SO_4 ha^{-1}; 0, 36 and 72 kg K ha^{-1}) on some physiological parameters of potato in different planting patterns (double-rows, dense double-rows and zigzag double-rows) during the 2016 and 2017 cropping seasons. The results showed that the planting pattern had a significant effect on leaf potassium content and tuber yield, with the greatest values observed in the zigzag pattern. There was a significant reduction in chlorophyll a and b, leaf potassium contents and tuber yield and an increase in the amount of proline and phenol when plants were supplied with 60% of their required water. Applying potassium sulphate helped plants maintain chlorophyll content under these conditions through enhancing potassium uptake. When plants faced water shortage conditions, the amount of soluble sugars increased, with the lowest increase in plants supplied with 150 kg ha^{-1} potassium sulphate. Using 150 kg K_2SO_4 ha^{-1} led to the greatest tuber yield (27 and 30 t ha^{-1} in the first and second year, respectively), while the lowest tuber yield (24 t ha^{-1} in both years) was produced without potassium application. In general, it seems supplying potato plants with potassium sulphate can alleviate, at least partly, harmful effects of water shortage.

Keywords Leaf potassium · Phenol · Photosynthetic pigments · Soluble sugars · Tuber yield

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Introduction

Water stress is one of the most important abiotic stresses that limit the growth and productivity of crops around the world (Reddy et al. 2004). The average annual precipitation of Iran is about 240 mm, one-third of the annual global value (Soltani et al. 2012). The stable production of potatoes in Iran, which has a cultivation area of about 159,000 ha with a total production of 4.7 million tonnes (FAO 2017), is severely limited by the persistence of drought stress due to the prevailing hot and dry climate in 90% of the country.

Water stress can affect all morpho-physiological aspects of potato plants due to their high sensitivity to the soil moisture shortages (Koech et al. 2015). It can severely reduce the chlorophyll content and limit the photosynthetic potential through secondary oxidative stress (Oliviera-Neto et al. 2009). Plants usually protect their cellular structure against reactive oxygen species (ROS) through producing a variety of enzymatic and non-enzymatic antioxidant compounds, such as phenol and proline (Rebey et al. 2012; Obidiegwu et al. 2015). In potato plants exposed to moisture stress, the increase in the leaf proline content may reach 1.6 (Teixeira and Pereiraa 2006) to 3.78 (Evers et al. 2010) times its level under normal conditions, depending on the severity of osmotic stress. Apart from other functions attributed to proline, such as ROS scavenger, osmoprotectant and signaling molecule (Kavi-Kishor et al. 2005), this huge increase in the proline content of potato plants under osmotic stress (Evers et al. 2010), and its relation with leaf water potential and relative water content (Knipp and Honermeier 2006), may indicate its role in osmotic regulation as a compatible solute. However, there is not always a definite correlation between proline accumulation and stress tolerance (Bündig et al. 2017), and there is still debate over whether proline really plays a role in drought tolerance of potato plants or is only a sign of stress in the plant (Obidiegwu et al. 2015). Another response of potato plants to osmotic stress is an increase in the concentration of soluble sugars in leaves (Evers et al. 2010; Folgado et al. 2013) that could have an osmoprotectant role against the harmful effects of drought stress in aerial parts of potato (Thapa et al. 2011).

Adopting some management strategies, including proper crop nutrition, can help alleviate impacts of water stress on crop productivity (Efeoğlu et al. 2009). Among all, potassium (K) is a macronutrient which is needed in large quantities by potatoes, generally more than N and P, for optimal production (Li et al. 2015; Schilling et al. 2016; Job et al. 2019). In a comprehensive study with data from 294 sites in China, it was shown that available K has the highest correlation with potato tuber yield, with the order of effect: K > N > organic matter > water > P (Wang et al. 2019). The critical exchangeable K value for potatoes has been reported in literature from 105 mg kg^{-1} for sandy loam, loam and clay loam soils in China (Li et al. 2015) to 224 mg kg^{-1} for volcanic soils in southern Chile (Sandaña et al. 2020). This variation can be largely due to differences in soil properties, including the soil organic matter content (Sandaña et al. 2020).

Potassium application positively affects photosynthesis and dry matter production under drought stress, through regulating stomatal movements and ionic balance and diminishing plant water losses (Marschner 1995; Saeed-Akram et al. 2009). It

also improves activity of many enzymes involved in photosynthesis and respiration processes (Doberman 2004; Wind et al. 2004), increases the chlorophyll content and carboxylation rate and prolongs leaf area duration (Marschner 1995; Doberman 2004). The contribution of K to the osmotic adjustment can decrease plant dependence on the activity of proline (Kanai et al. 2007) and soluble sugars (Fayez and Bazaid 2014), even leading to their reduction in the plant. Application of K fertilizer can also increase other macronutrients and carbohydrates in the leaves of potato plants and stimulate protein synthesis and transport of assimilates (Ali et al. 2021). Such positive effects of K on the above-mentioned physiological processes directly affect plant growth, resulting in higher leaf area, delayed leaf senescence and increased plant height, and consequently improved tuber formation and yield (for a review, see Bishwoyog and Swarnima 2016; Torabian et al. 2021).

Achieving high yields in potatoes depends a lot on optimizing the plant density and spatial arrangement (Akassa et al. 2014) that can lead to proper distribution of light, water, and nutrients among plants (Ashraf et al. 2008). One of the conventional potato planting systems in Iran is double rows per wide ridge. This type of planting system is generally used to optimize crop productivity in which the distance between double rows is narrower than the distance between two rows in a single-row system. However, the open space to the next ridge allows each plant to receive more light (Alimuddin et al. 2020). It has been observed that maximum potato yield is achieved in the double row system (10 cm spacing between rows within a pair and 50 cm spacing between one pair and the next), in comparison with 50 cm apart single-rows (Mahmood 2005). An alternative method is planting in double rows alternately (i.e. in a zigzag pattern), which can reduce competition between plants. In sweet potatoes, using zigzag twin-rows has been shown to produce approximately 30% higher yields than a single-row system (Balázs et al. 2021). In potatoes, it has also been reported that both tuber number and yield were higher in the zigzag system (alternating planting in double-rows on 66-cm ridges) than in the conventional method (double-rows on 75-cm ridges) (Kokuryu et al. 2016). It should be noted that changes in plant density in any of these systems can reduce or increase the average tuber number, size and yield (Tarkalson et al. 2011; Binalfew et al. 2015; Zheng et al. 2016), largely depending on the level of soil water supply (Bernik et al. 2010).

Considering the importance of potatoes in feeding the world as well as the climatic conditions of Iran as an arid and semi-arid country, and prediction of more water constraints in the future, it is a vital necessity to study the effects of drought stress on potatoes. Despite the importance of potassium in potato plant nutrition, this element is not usually considered in fertilizing programs, or used only in small amounts in Iran. Thus, this study was performed to determine if a proper planting pattern and potassium amounts can help potato plants withstand damaging effects of water deficit.

Materials and Methods

A 2-year study was conducted during the 2016 and 2017 cropping seasons in the Jolgeh Rokh Plain, Khorasan Razavi, Iran, located at 59° 29′ E and 35° 38′ N, with an elevation of 1600 m above sea level with an annual rainfall of 225 mm. The

Table 1 Daily values of maximum and minimum air temperature (°C) and precipitation (mm) for 2016 and 2017 in Jolgeh Rokh Plain, Khorasan Razavi, Iran (59° 29′ E, 35° 38′ N)

Month	Maximum temperature (° C)		Minimum temperature (° C)		Rainfall (mm)	
	2016	2017	2016	2017	2016	2017
June	28.35	27.90	13.30	14.70	8.1	1.9
July	29.23	28.01	16.10	14.44	0	3.2
August	28.36	27.47	14.87	13.60	0	0
September	27.94	25.55	13.32	10.92	1.6	1.9
October	23.06	21.46	8.35	7.10	3.0	1.0
Average/ Total	27.39	26.00	13.31	12.18	12.7	8.0

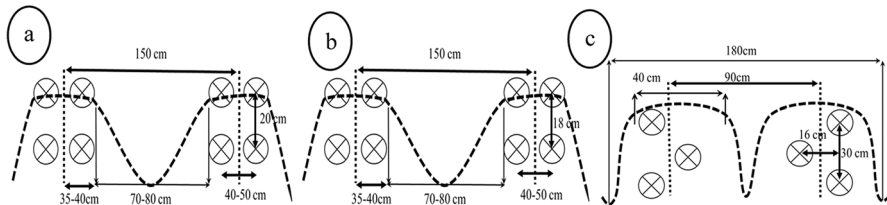**Fig. 1** (a) Double-rows, (b) dense double-rows and (c) zigzag double-rows planting patterns used in the experiment. ⊗ Shows planted tubers

weather data are presented in Table 1. The research was performed as a split-split plot experiment based on a randomized complete block design with three replications in a field that was under wheat cultivation the previous year. Treatments consisted of three planting patterns [double-rows (DR), dense double-rows (DDR) and zigzag double-rows (ZDR)] as the main plot (Fig. 1), three irrigation regimes [irrigating plots with 100 (control, non-stressed), 80 (as deficit irrigation) and 60% (as stressed) of crop water requirement (CWR)] as subplots, and potassium fertilizer in three levels (0, 75 and 150 kg K_2SO_4 ha^{-1} (equal to 0, 36 and 72 kg K ha^{-1}, respectively) as sub-subplots. The size of plots in DR and DDR was 3 × 6 m and in ZDR 3.6 × 6 m. In the DR pattern, tubers were planted 0.2 m apart in two rows (0.4–0.5 m apart) on wide ridges (1.5 m) with a plant density of 6.6 pl m^{-2}) (Fig. 1a). A similar pattern was used in DDR, except that the distance between tubers was reduced to 0.18 m (7.4 pl.m^{-2}) (Fig. 1b). In the ZDR pattern, tubers were planted 0.3 m apart alternately (rows 0.16 m apart) on both sides of 1.8 m wide ridges (7.4 pl.m^{-2}) (Fig. 1 c). A ridge was left unplanted between two subplots to prevent lateral water penetration.

Before planting, soil samples from the experimental site were taken, and their physical and chemical properties were determined (Table 2). Potato seed tubers of variety Agria were taken from Khazaee Agricultural, Livestock Breeding and Animal Husbandry Complex (http://kh-corp.com/en/home/) and hand planted on 24 June 2016 and 19 June 2017. Potassium sulphate fertilizer was also planted at the same time in strips near tubers, and then all plots were fully and uniformly irrigated. Different irrigation regimes were applied after plant emergence. During the crop growth cycle, weeds were controlled by hand-weeding, and pest control

Table 2 Physico-chemical analysis of the experimental site soil (0–30 cm depth)

Depth (cm)	Clay	Silt	Sand	P	K	N	pH	Ec	Organic matter	T.N.V.
	------------ (%) ------------			---------- (mg/kg) ---------		(%)		(dS/m)	---------- (%) ----------	
0–30	14	30	56	16.4	297	0.033	7.8	1.48	0.38	16.8

was conducted according to the recommendations of the local Agricultural Extension Office, Ministry of Agriculture.

The crop water requirement was determined using OPTIWAT software based on the FAO Penman-Monteith method (Alizadeh and Kamali 2007). In order to determine the irrigation times, soil moisture content was monitored frequently by taking soil samples at a depth of root development; then, soil moisture depletion relative to field capacity was determined by weight difference of soil samples before and after oven drying and using the moisture curve. All treatments were irrigated after 35–40% soil moisture depletion. The volume of water required for each irrigation level was also calculated using Eq. (1) (Alizadeh 2006):

$$V = A.B.M (F - W)(D) \tag{1}$$

where V is the volume of water to be applied (cm^3); A is the plot area (cm^2); B is the soil bulk density (g cm^3); M is the percentage of soil moisture depletion allowed (35–40%); F and W are gravimetric water percentage at field capacity and wilting point, respectively; and D is the depth of root development. Irrigation was done using a drip tape method, and the total amount of water entered into each plot was measured using a volumetric flow meter.

In order to measure biochemical parameters, leaf samples were taken from an identical height of plants in the middle of the tuber bulking stage. The sampled leaves were washed with distilled water, and then sample discs were taken from the leaf blade, between midrib and leaf margin, and then immediately frozen using liquid nitrogen, and kept at − 70 °C in microtubes. The leaf samples were later used to measure leaf proline content (0.5 g fresh tissue; Bates et al. 1973), soluble sugars (0.2 g fresh tissue; Schlegel 1956), total phenol content (2.5 g dry tissue; Shehab et al. 2010), photosynthetic pigments (0.1 g fresh tissue; Lichtenthaler 1987) and leaf potassium content (1 g fresh tissue; Cottenie 1980). To measure tuber yields, each experimental plot was harvested individually 110 and 117 days after planting dates in 2016 and 2017, respectively.

After excluding the green and deformed ones, the tubers of 10 plants were passed through a sieve with a 40-mm mesh. Those healthy tubers larger than 40 mm were counted as marketable tubers. The non-marketable tubers included ones smaller than 40 mm and green or deformed ones (Vučajnk et al. 2017).

All data were statistically analysed by analysis of variance using SAS (V. 9.4), and means were compared using Fisher's least significant difference (FLSD) test at 5% probability level. As the combined analysis assumptions were not met for tuber yield based on the Bartlett test, this trait was analysed separately for each

experimental year. In other words, the Bartlett test indicated that the variances of errors were not homogeneous for tuber yield in the 2 years of this study; therefore, the combined analysis of variance was not performed for this trait.

Results and Discussion

The statistical analysis of the results showed a significant effect of irrigation (I) and potassium (K) levels on all traits ($P < 0.01$). The effect of planting pattern (P) was significant only on leaf K and phenol ($P < 0.05$), non-marketable tubers ($P < 0.01$) and tuber yield in both years ($P < 0.01$). Only phenol and soluble sugars ($P < 0.01$) and marketable and non-marketable tubers ($P < 0.05$) were significantly different between the 2 years. Where no significant effects were observed for interaction effects of I and P, except for marketable and non-marketable tubers, I and K interaction effect was significant on all traits, except for the tuber yield of the second year. The interaction of I, P and K significantly affected leaf K content and marketable tubers ($P < 0.01$) and marketable tubers and tubers yield in 2016 ($P < 0.05$) (Table 3).

Proline

The greatest proline content was observed in plants irrigated at 60% of CWR in the first year, and there was no significant difference in the full irrigation (100% CWR) treatment between the two years (Table 4). The lower maximum temperatures in the second year (Table 1), and consequently mitigating synergistic effect of heat and water shortage (Lehretz 2020), may be involved in lower proline levels in the second year. Increased accumulation of proline and its analogues in potato leaves has been reported by several other authors as one of the obvious responses of plants to water stress (Teixeira and Pereira 2006; Evers et al. 2010; Kumar and Minhas 2013; Kumar et al. 2020) which shows that these compounds are apparently related to stress tolerance. It has been observed that proline content increases significantly in response to water stress imposed at different growth stages (tuber initiation, elongation and maturation stages), compared to well-irrigated control (Kumar et al. 2020). According to Ariza et al. (2020), the proline content of potato plants under water-deficit stress was several times higher than that of fully irrigated plants. They stated that this increase in proline synthesis helped the plants to maintain their water status during water shortage period and prevented a reduction in RWC. However, although the more tolerant potato genotype in the Bündig et al. (2017) study accumulated proline faster and had a higher overall osmotic potential under osmotic stress, they demonstrated that these raised levels of proline should be considered more as an overall plant response to osmotic stress than as a biochemical marker to discriminate between susceptible and resistant genotypes. As a response to potassium application, the increase in proline under water deficit was lower where plants were supplied with K. The highest proline content was observed when plants were supplied with 60% CWR and no potassium, while using 72 kg K ha^{-1} reduced the

Table 3 Analysis of variance on selected traits of potato, cv. Agria, as affected by planting patterns, irrigation levels, and application of potassium sulphate fertilizer in Jolgeh Rokh Plain, Iran

Source of variance	df	Mean squares						Tuber no.		df	Tuber yield[§]	
		Chl. a	Chl. b	Proline	Total phenol	Soluble sugars	Leaf K	Marketable	Non-marketable		2016	2017
Replication (R)	--	--	--	--	--	--	--	--	--	2	0.94	14.14
Year (Y)	1	8.26^{ns}	0.84^{ns}	1.38^{ns}	1479.13**	21151**	0.01^{ns}	322.29*	34.79*	--	--	--
Rep. * Y	4	1.67^{ns}	3.50*	1.03^{ns}	49.50^{ns}	594.01^{ns}	0.06^{s}	41.51^{ns}	2.85^{ns}	--	--	--
Planting pattern (P)	2	0.22^{ns}	0.83^{ns}	2.41^{ns}	297.54*	129.51^{ns}	0.80*	41.56^{ns}	152.09**	2	212.81**	383.95**
Y * P	2	0.79^{ns}	0.48^{ns}	0.21^{ns}	29.27^{ns}	11.27^{ns}	0.36^{ns}	51.15^{ns}	43.05*	--	--	--
Error a	8	1.02	0.54	0.66	50.08	634.93	0.106	33.43	7.57	4	1.56	17.53
Irrigation (I)	2	118.78**	18.58**	32.44**	10091**	264928**	27.26**	2072.35**	223.78**	2	1023.49**	1622.56**
Y * I	2	0.51^{ns}	0.54^{ns}	1.33*	64.43^{ns}	5621.21**	0.18^{ns}	26.06^{ns}	20.70*	--	--	--
P * I	4	0.29^{ns}	0.72^{ns}	0.56^{ns}	110.91^{ns}	712.74^{ns}	0.13^{ns}	36.88**	47.41**	4	4.71^{ns}	7.29^{ns}
Y * P * I	4	1.60^{ns}	0.19^{ns}	0.49^{ns}	110.26^{ns}	605.98^{ns}	0.08^{ns}	41.17**	12.21*	--	--	--
Error b	24	0.91	0.52	0.36	75.18	417.79	0.08	7.65	4.16	12	1.06	12.64
Potassium (K)	2	25.83**	9.31**	6.86**	2159.10**	48748*	12.29**	1623.44**	422.18**	2	44.44**	242.20**
Y * K	2	2.21**	0.19^{ns}	0.08^{ns}	79.95^{ns}	261.19^{ns}	0.22*	16.29^{ns}	7.70*	--	--	--
P * K	4	0.38^{ns}	0.10^{ns}	0.33^{ns}	58.32^{ns}	237.04^{ns}	0.167*	35.14**	26.99**	4	18.20**	31.94**
Y * P * K	4	0.23^{ns}	0.45^{ns}	0.03^{ns}	21.69^{ns}	488.83^{ns}	0.02^{ns}	46.24**	16.02	--	--	--
I * K	4	2.45**	1.16**	1.93**	230.22**	4368.74**	0.17	51.16**	19.89**	4	20.52**	15.83^{ns}
Y * I * K	4	0.78*	0.08^{ns}	0.03^{ns}	47.45^{ns}	787.36^{ns}	0.27**	3.46^{ns}	3.16^{ns}	--	--	--
P * I * K	8	0.27^{ns}	0.24^{ns}	0.49^{ns}	41.48^{ns}	285.63^{ns}	0.30*	12.55*	9.26**	8	8.30*	8.61^{ns}
Y * P * I * K	8	0.51^{ns}	0.19^{ns}	0.10^{ns}	45.20^{ns}	445.24^{ns}	0.11^{ns}	23.52**	9.59**	--	--	--
Error c	72	0.26	0.23	0.27	30.9	727.66	0.06	6.02	2.03	36	3.05	9.92

^{ns}, **, and * represent non-significant, and significant at the 0.01 and 0.05 probability level, respectively

[§]Because the combined analysis assumptions were not met for tuber yield, analysis of variance of this trait was performed separately for either experimental year

Table 4 Changes in proline, soluble sugars and total phenol contents in potato plants leaves in response to irrigation regimes (supplying 100, 80 and 60% of crop water requirement, CWR) in two successive years (2016 and 2017) and/or different potassium rates [0, 36 and 72 kg K ha^{-1})]

	Irrigation (supplying CWR)	Year		Potassium (kg K ha^{-1})		
		2016	2017	0	36	72
Proline	100%	3.47[d]	3.71[d]	3.57[e]	3.63[e]	3.58[e]
	80%	4.31[c]	4.77[b]	5.06[b]	4.52[cd]	4.03[de]
	60%	5.21[a]	5.05[ab]	5.77[a]	4.97[bc]	4.65[bc]
Soluble sugars	100%	70.89[d]	71.37[d]	83.27[f]	71.96fg	58.17g
	80%	192.27[b]	160.60[c]	208.44[b]	186.86[c]	134.01[e]
	60%	222.48[a]	185.12[b]	241.87[a]	206.73[b]	162.80[d]
Phenol	100%			27.37[e]	28.07[e]	20.95[f]
	80%			54.95[ab]	43.47[c]	36.22[d]
	60%			58.47[a]	51.34[b]	45.70[c]

For each trait, non-similar letters indicate a statistically significant difference at 0.05 probability level based on FLSD test, in interactions between irrigation and year, and between irrigation and potassium. The interaction between irrigation and year was not significant for phenol based on table of analysis of variance (Table 3)

proline content about 20% in both 80 and 60% CWR treatments (Table 4). In the study of Abd El-Gawad et al. (2017), the lowest free proline content was observed in the leaves of control plants (irrigated at 55–60% of soil water depletion) along with foliar application of 2000 ppm potassium silicate. They attributed this reduction in proline content to the synergistic effect of potassium silicate and water stress on different biochemical pathways in the plant cell.

K has been shown to have positive effects on the activity of antioxidant enzymes (Ma et al. 2004), activity of nitrate reductase (Doberman 2004) and/or osmotic adjustment through facilitation of water uptake by plants (Kanai 2007). Therefore, one of the roles of potassium in plants under water-deficit conditions, at least in this experiment, could be considered as helping in osmoregulation through involvement in the synthesis of osmolytes, thus enabling plants to cope with stress and to maintain turgor pressure. Reduced proline content under drought stress in response to potassium application has also been reported in *Brassica* species (Sharma and Kuhad 2006) and tobacco (Norastehnia and Valeh 2016).

Soluble Sugars

The minimum concentration of soluble sugars in both years was obtained in plants supplied with 100% CWR, while the greatest concentrations were observed in 60% CWR treatment in the first year (Table 4). In fact, the increased rate of concentration of soluble sugars in the 60 and 80% CWR, compared to the 100% CWR, was 213.8% and 171.2% in the first year and 159.4% and 125.0% in the second year, respectively (Table 4). The results revealed that the accumulation of soluble sugars has been increased under water stress conditions at all potassium rates; however, where no potassium was applied, an increase in soluble sugars content was observed at all

irrigation levels. In general, the highest concentration of soluble sugars was obtained at 60% CWR and no potassium application (Table 4). Such an increase in the soluble sugars concentration, which has also been reported by Folgado et al. (2013), may be a result of starch hydrolysis (Li et al. 2013) or increased activity of sucrose phosphate synthase (Plaue et al. 2004) during water stress. Moreover, reduced export of sucrose out of the leaves leads to an increase in soluble carbohydrates, as has been observed under short- and long-term soil water shortages (Pereira and Chaves 1993). These accumulated soluble sugars can act as osmoprotectants against the detrimental effects of drought stress in potato shoots (Thapa et al. 2011), but on the other hand, the accumulation of sugars in the leaves can disturb photosynthesis through a feedback inhibition mechanism, reducing biomass production (McCuea and Hanson 1990).

Application of potassium fertilizer reduced, and even ceased, the increase in soluble sugars, which could be due to the role of potassium in enhancing photosynthesis through improving turgor pressure and stomatal conductance (Reddy et al. 2004; Sharma and Kuhad 2006). Also, by facilitating the translocation of soluble sugars, potassium can play an essential role in regulating osmotic pressure and maintaining turgor of root cells and reducing the sugar accumulation in the leaves (Fayez and Bazaid 2014).

Total Phenol

Total phenol content in the first year was 16% greater than in the second year (Table 5). Plants in the DR and DDR planting patterns had a greater total phenol content than in the ZDR pattern (Table 5). Regarding the interaction effect of irrigation and potassium sulphate fertilizer, when plants were irrigated with 80 and 60% of their CWR, supplying them with 72 kg K ha^{-1} reduced their total phenol by 34% and 21.8%, respectively, compared with non-fertilized plants (Table 4). The highest phenol content was observed in plants irrigated with 60% CWR without potassium fertilization (Table 4). The reason for this may be due to the stimulatory role of potassium in increasing antioxidant enzyme activity, which counteracts free radicals and in turn leads to a decrease in the production

Table 5 Mean comparisons for the simple effects of year, planting pattern, irrigation and potassium fertilizer on phenolic compounds of potato leaves

Treatments	Year		Planting pattern[§]			Irrigation (supplying CWR[†])			Potassium (kg K ha^{-1})		
	2016	2017	DR	DDR	ZDR	100%	80%	60%	0	36	72
Phenol (mg g^{-1} DW)	43.74	37.7	40.91	42.97	38.28	25.46	44.87	51.83	46.92	40.95	34.28
LSD$_{(0.05)}$	3.06		3.14			3.44			2.13		

[§]DR, DDR and ZDR stands for double-rows, dense double-rows and zigzag double-rows planting pattern, respectively

[†]CWR indicates crop water requirement

of phenols in the plant (Norastehnia and Valeh 2016). In general, limited irrigation levels increased phenolic content of plants relative to full irrigation. Increase in phenolic compound production is one of the antioxidant defense mechanisms of plants faced with drought stress (Bettaieb et al. 2011; Rebey et al. 2011). Phenolic compounds can act as scavengers to eliminate ROSs and thereby stabilize cell membranes and inhibit the peroxidation of lipids (Chang et al. 2002). It has been reported that these compounds, through affecting some leaf properties such as the number of stomata, can even reduce plant transpiration and increase the plant's resistance to drought stress (Buttery et al. 1993).

Chlorophyll a

The highest and lowest contents of chlorophyll a were obtained in the first year from supplying 100% CWR with 72 kg K ha^{-1}, and 60% CWR with zero K fertilizer, respectively (Table 6). Although limiting water application from 100 to 60% CWR reduced chlorophyll a at all potassium levels in both years, it seems that fertilizing plants with potassium mitigates the impacts of water deficit and increases chlorophyll a content.

Under non-K fertilized conditions, the reductions in chlorophyll a content due to reducing supplied water from 100 to 60% of CWR were 60.6 and 47.5% in the first and second year, respectively, while these reductions dropped to 27.2 and 35.4%, respectively, where plants were supplied with 72 kg K ha^{-1} (Table 6).

Chlorophyll b

Decreasing supplied water reduced chlorophyll b content at all potassium levels (Table 6). Using 72 kg K ha^{-1} along with supplying 100% CWR resulted in the highest level of chlorophyll b in plants. Preserving chlorophyll content under drought stress is one of the important physiological indices of plant resistance (Pessarkli

Table 6 The comparison of changes in chlorophyll a and b content in potato plant leaves in response to irrigation regimes (supplying 100, 80 and 60% of crop water requirement, CWR) at different potassium rates (0, 36 and 72 kg K ha^{-1})

		Chl a						Chal b		
		2016			2017					
Irrigation (providing CWR)		100	80	60	100	80	60	100	80	60
Potassium (kg K ha^{-1})	0	6.90[bcd]	5.62[g]	2.72[k]	6.55[de]	5.29[gh]	3.44[j]	2.99[bc]	1.91[f]	1.69[f]
	36	7.17[bc]	6.68[de]	4.51[i]	6.76[cd]	5.77[fg]	3.76[j]	3.02[b]	2.70[bcd]	2.35[e]
	72	7.76[a]	7.01[bcd]	5.66[g]	7.28[ab]	6.26[ef]	4.86[hi]	3.88[a]	2.69[cd]	2.50[de]

For each trait, the similar letters do not have a statistically significant difference at 0.05 probability level based on LSD test

1999). Typically, as water stress intensifies, leaf chlorophyll content is reduced (Jaleel et al. 2008), which might be attributed to the destruction of chloroplast and photosynthetic apparatus, chlorophyll phyto-oxidation, degradation of precursors of chlorophyll synthesis and prevention of new chlorophyll biosynthesis, activation of chlorophyll hydrolyzing enzymes such as chlorophyllase, and/or hormonal disorders (Thalooth et al. 2006; Neocleous and Vasilakakis 2007). It has been reported that drought stress is a significant factor in reducing the production and stability of the most important photosynthetic pigment (chlorophyll) in potato (Farooq et al. 2009).

While the lowest level of chlorophyll b was observed in 60% CWR with no potassium application, applying 72 kg K ha^{-1} at the same moisture level increased chlorophyll b content by 48% (Table 6), which is probably due to the role of potassium in the synthesis of chlorophyll precursors and suppression of ROSs (Liu et al. 2014). It is known that under drought stress conditions, potassium usage improves the activity of nitrate reductase and increases chlorophyll content and regulates stomata openness, which in turn leads to an increase in the photosynthesis rate and carbon fixation, leaf area duration and dry matter production (Marschner 1995; Doberman 2004).

Leaf Potassium Content

Plants supplied with 100% CWR and 72 kg K ha^{-1} in the DR and ZDR planting patterns had the highest potassium contents in their leaves, whereas the DR and DDR patterns along with supplying 60% CWR and zero potassium presented the lowest amounts of potassium in the leaves (Table 7). In general, the leaf potassium content decreased with reducing irrigation water levels, which is a usual phenomenon of drought stress (Cakmak 2005). Under unfavorable conditions, potassium can play an essential role in regulating cell metabolism, so its high levels can help plants to withstand osmotic stress (Cakmak 2005), especially because potassium is effective in preserving rates of carbon fixation during photosynthesis. Stomatal closure in response to drought stress, while reducing CO_2 fixation, stimulates generation of reactive oxygen species whose formation can be exacerbated under potassium deficiency (Vyas et al. 2001). Potassium also plays a crucial role in protein synthesis, photosynthesis rate and the transfer of the photosynthates (Kanai et al. 2007). In the present study, the amount of leaf potassium showed a significant decrease in plants supplied with 80 and 60% of CWR, compared to the control plants (100% CWR). Yet, using potassium fertilizer raised the amount of leaf potassium, so that under supplying 60% of CWR, applying 72 kg fertilizer ha^{-1} increased leaf potassium content in all planting patterns (Table 7). In agreement with these results, Norastehnia and Valeh (2016) found that potassium concentration of tobacco plants decreased significantly under water stress, while potassium consumption increased potassium concentration in the leaves. It has been shown that the application of high levels of potassium fertilizers in potato plants increase their uptake to a level more than the plant requirement level (Kang et al. 2014).

Table 7 Interaction effects of planting pattern, irrigation regimes (supplying 100, 80 and 60% of crop water requirement, CWR) and potassium (0, 36 and 72 kg K ha^{-1}) on leaf potassium content and tuber yield of potato in 2016

Irrigation (providing CWR)	Potassium (kg K ha^{-1})	Leaf potassium content (%)			Yield (t ha^{-1})		
		DR[§]	DDR	ZDR	DR	DDR	ZDR
100%	0	5.1	5.1	5.2	28.6	29.7	36.7
	36	5.1	5.5	5.7	31.8	30.9	36.7
	72	6.3	5.8	6.2	31.2	31.1	36.3
80%	0	4.1	4.1	4.4	23.0	21.5	25.3
	36	4.6	4.6	4.6	24.1	19.0	25.3
	72	4.9	5.3	5.2	21.0	21.4	27.6
60%	0	3.4	3.5	3.8	15.9	18.2	20.5
	36	4.3	4.0	4.3	18.1	18.7	21.0
	72	4.8	4.4	4.7	20.9	18.3	30.2
LSD $_{(0.05)}$			0.28			2.9	

[§]DR, DDR and ZDR stands for double-rows, dense double-rows and zigzag double-rows planting pattern, respectively

Number of Marketable and Non-Marketable Tubers

The number of non-marketable tubers in the first year was 12% higher than in the second year, which may be due to the higher average maximum temperature in the first year (Table 8). In addition to affecting tuber yield, high temperatures can change the large to small tubers ratio, increasing the number of non-marketable tubers by reducing the allocation of photosynthates to the tubers (Kim et al. 2017).

Reducing the irrigation level to 80 and 60% CWR increased the number of non-marketable tubers by 44.5% and 68.2%, respectively, compared to 100%. A decrease in the number of marketable tubers was observed with decreasing water supply in all cultivation patterns and in both cropping years (Table 8). The results of Onder et al. (2005) also showed that water shortage can reduce the number and size of tubers, and conversely, proper irrigation leads to the formation of larger tubers. On the other hand, the application of 72 kg K ha^{-1} reduced the number of non-marketable tubers in 100, 80 and 60% CWR by 43.11, 55.88 and 45.26%, respectively (Table 8). This positive effect of K on the number of marketable tubers was evident in all three cropping patterns and in both cropping years, especially at low irrigation levels.

In general, the DDR pattern had the highest and the ZDR one the lowest number of non-marketable tubers (Table 8). Decrease in average tuber size with increasing plant population (Tarkalson et al. 2011; Zheng et al. 2016) could be the reason for the higher number of non-marketable tubers in DDR. A reduction in irrigation water, K levels, or both, led to an increase in number of non-marketable tubers in all cultivation patterns (Table 8). It has been found that the response of potato plants to planting arrangement depends on the level of water supply (Bernik et al. 2010). In our study, the highest number of non-marketable tubers was in the first year in DDR pattern under 60% CWR and no potassium fertilizer, and the lowest in the second year in ZDR with 100% CWR and 36 kg K ha^{-1}. At 60% CWR, using 72 kg K ha^{-1} decreased the number of non-marketable tubers in the DR, DDR and ZDR

Table 8 The comparison of changes in marketable (> 40 mm) and non-marketable (< 40 mm) potato tubers in response to interaction of irrigation regimes (supplying 100, 80 and 60% of crop water requirement, CWR), potassium rates (0, 36 and 72 kg K ha^{-1}) and planting patterns in two year

Planting pattern			DR[$]			DDR			ZDR		
Irrigation (supplying CWR)			100%	80%	60%	100%	80%	60%	100%	80%	60%
	Year	Potassium (kg K ha^{-1})									
Non-marketable tubers (no.m^{-2})	2016	0	5.7	14.7	13.1	14.6	15.9	17.4	6.7	6.7	11.7
		36	5.8	4.4	11.7	10.7	12.0	7.3	2.2	5.2	6.9
		72	4.7	7.4	12.7	7.2	5.0	6.0	4.4	3.1	7.8
	2017	0	7.1	14.0	13.3	8.3	11.1	12	4.3	10.0	14.8
		36	4.4	12.0	10.0	7.6	9.1	7.8	2.0	5.7	6.9
		72	3.6	8.7	7.3	3.8	3.7	5.8	2.9	3.9	5.6
LSD $_{(\%5)}$: 2.84											
Marketable tubers (no.m^{-2})	2016	0	30.6	15.0	12.9	22.1	12.4	5.8	26.1	21.7	15.8
		36	31.2	28.2	15.6	27.0	21.1	21.7	31.9	23.7	21.4
		72	33.3	26.6	19.7	31.4	32.3	25.3	31.1	29.6	22.5
	2017	0	22.4	10.6	8.0	23.6	14.8	9.7	24.9	11.6	5.3
		36	27.5	14.6	16.2	24.8	21.9	15.5	32.2	22.5	15.0
		72	32.4	20.0	21.7	32.6	28.6	21.5	31.3	27.9	21.4
LSD $_{(\%5)}$: 3.99											

[$]DR, DDR and ZDR stands for double-rows, dense double-rows and zigzag double-rows planting pattern, respectively

planting patterns by 7.7%, 68.5% and 34.0% in the first year and by 45.0%, 51.9% and 62.5% in the second year, respectively (Table 8). Various researchers have demonstrated the high K requirement of potatoes for high production of marketable tubers (Khan et al. 2012; Singh and Lal 2012; Ali et al. 2021), which may be due to the positive function of K in activating enzymes involved in photosynthesis and carbohydrate synthesis and facilitating the transfer of photosynthates from the leaves to the tubers (Karam et al. 2011; Tränkner et al. 2018). The observed negative correlation between the number of non-marketable tubers and the total tuber yield ($r = -0.58^{**}$) also indicates that the inability of plants to provide tubers with adequate photosynthates is a main reason for the increase in the number of small-sized tubers and yield reduction under water and potassium shortage.

Tuber Yield

With a shift in planting pattern from DR to ZDR, tuber yield showed a significant increase in plants received potassium and 100% of CWR. The potato plants grown in the ZDR pattern at 100% CWR with 36 and 72 kg K ha^{-1} produced 130% greater tuber yield than those planted in the DR planting pattern with only 60% of CWR without potassium fertilizer (Table 7). Generally, where plants were supplied with 100% CWR and 72 kg K ha^{-1}, planting in a ZDR pattern caused about 17% more tuber yield than the DR and DDR planting patterns. This indicates that the more uniform the plant distribution, the less shading and competition for radiation. This uniform arrangement of plants in the field would lead to greater yields, provided an optimum supply of inputs, especially water. Higher grain yields of corn have been reported in two-row ZDR planting pattern than in single-row cropping (Ramezani and Rezaei Sokht-Abandani 2013).

With decreasing irrigation rates in all planting patterns and potassium rates, the tuber yield showed a reduction (Table 7). Potato yield depends a lot on canopy structure as well as yield components such as number and average size of tubers, all of which are affected by deficit irrigation during the crop cycle (Al-Mahmud et al. 2014). Possibly, when plants are exposed to water stress, the stomatal resistance of their leaves increases and leaf area and photosynthesis rate decrease, resulting in a reduction in aboveground biomass, tuber growth and finally tuber yield (Irna and Mauromicale 2006).

The total gains of tuber yield from the usage of 72 kg K ha^{-1} compared with none in the DR, DDR and ZDR planting patterns were 9.0, 4.9 and 13.0%, respectively, at 100% of CWR, and 31.6, 0.5 and 47%, respectively, at 60% of CWR (Table 7). As potassium plays an essential role in the assimilation and translocation of assimilates to the developing organs, sufficient amounts can help the maintenance of photosynthesis and the production of photosynthetase when plant faces water deficit (Abbasi Moghaddam et al. 2014).

The ZDR planting pattern along with 72 kg K ha^{-1} produced the highest tuber yields, and dense DDR with 0 and/or 36 kg K ha^{-1} produced the lowest (Table 7). Using 72 kg K ha^{-1} led to the greatest tuber yield (27 and 30 t ha^{-1}

in the first and second year, respectively), while the lowest tuber yield (24 t ha^{-1} in both years) was produced without potassium application. It also caused enhanced tuber yields in all planting patterns, and the rate of this increase was 10.2%, 28.1% and 35.5% for the DR, DDR and ZDR patterns, respectively. It is clear that in both years, plants in the ZDR pattern showed a better response to potassium than the two other patterns. It is likely that in the ZDR planting pattern, the distribution of above- and under-ground plant parts was more suitable, thus allowing a plant to have more efficient usage of inputs, including potassium. Using potassium prevented further reduction of potato tuber yield even at 60% of CWR in both years. It seems that as soil moisture content decreases, potassium can help stressed plants (water stress) to partly reduce yield losses. Hannan et al. (2011) also reported that potato yield improved with increasing potassium usage. It has been stated that potassium, on the one hand, increases the strength of potato stems, and as a result improves tuber yield and quality, and on the other hand makes plant adapted to environmental stresses (Kang et al. 2014).

Conclusions

In this field research, we investigated some physiological responses of potato plants to changes in planting pattern at variable levels of potassium fertilizer and irrigation. Our results revealed that the amounts of proline, phenol, soluble sugars, potassium and photosynthetic pigments of potato leaves change in response to irrigation water level and potassium fertilizer rates. Among these traits, leaf potassium content was affected by the planting pattern, so the highest percentage of leaf potassium was observed in zigzag double-rows (ZDR) one. There was a reduction in leaf chlorophyll and potassium contents by reducing irrigation water from 100 to 60% of crop water requirement (CWR). Furthermore, the greatest chlorophyll and potassium contents were observed in plants supplied with 100% CWR and 72 kg K ha^{-1}. The highest proline, soluble sugars and phenol contents were obtained in those plants irrigated at 60% CWR, and application of potassium reduced their concentration significantly. In general, plants in the ZDR pattern produced a higher yield than two other planting patterns, especially under water-deficit conditions. According to our results, it can be concluded that the best planting pattern for potato, in respect to tuber yield and number of marketable tubers, is a ZDR pattern, with approximately the same distance between plants from the four sides. On the other hand, despite the sensitivity of potato plants to water shortage, the use of potassium fertilizer improved plant tuber yield and number of marketable tubers in all planting patterns and irrigation levels, especially in plants provided by 60% of crop water requirements (water stressed plants).

Declarations

Ethics Approval There was no human or animal experimentation involved.

Conflict of Interest The authors declare no competing interests.

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