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Water Regimes and Humic Acid Application Influences Potato Growth, Yield, Tuber Quality and Water Use Efficiency

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Abstract This study assessed effects of irrigation water regimes and humic acid (HA) application on vegetative growth, yield, tuber quality and water use efficiency (WUE) of potato. Five irrigation treatments were applied at three developmental stages; (WR1) control (100 % crop evapotranspiration, 100 % ETc) at all plant growth, (WR2) 75 % ETc at all stages, (WR3) 75 % ETc at stage S1 (vegetative growth), (WR4) 75 % ETc at stage S2 (tuber initiation), and (WR5) 75 % ETc at stage S3 (tuber bulking). HA was applied at a rate of 1.5 g L^{-1} 30 day after seed pieces planting. Plants experiencing water stress at S1 were shorter with fewer branches and lower fresh and dry vine weights. Water stress imposed at S2 significantly reduced tuber number, size, and yield. HA application increased vegetative growth, tuber weight, yield, WUE, and tuber quality (specific gravity and starch content). Thus, applying 1.5 g L^{-1} HA during vegetative growth and a 75 % ET water regime at S3 can increase potato production and tuber quality while reducing water use.

Resumen En este estudio se evaluaron los efectos de los regímenes de agua de riego y la aplicación del ácido húmico (HA) en el crecimiento de la planta, rendimiento, calidad de tubérculo y la eficiencia del uso del agua (WUE) de la papa. Se aplicaron cinco tratamientos de riego en tres estados de desarrollo; (WR1) testigo (100 % evapotranspiración del cultivo, 100 % ETc) a todo el crecimiento vegetativo, (WR2) 75 % ETc en todas las etapas, (WR3) 75 % ETc en la etapa S1 (crecimiento vegetativo), (WR4) 75 % ETc en la etapa S2 (iniciación de tubérculo), y (WR5) 75 % ETc en la etapa S3 (llenado de tubérculo). Se aplicó HA a un nivel de 1.5 g*L-1 30 días después de la siembra de las unidades de semilla. Las plantas que experimentaron agobio hídrico en S1 fueron más cortas con menos ramas y pesos más bajos fresco y seco del follaje. El agobio hídrico impuesto en S2 redujo significativamente el número de tubérculos, el tamaño y el rendimiento. La aplicación de HA aumentó el crecimiento vegetativo, el peso de tubérculo, el rendimiento, WUE, y la calidad del tubérculo (gravedad específica y contenido de almidón). De aquí que la aplicación de 1.5 g*L-1 de HA durante el crecimiento vegetativo y un régimen de agua de 75 % de ET en S3 puede aumentar la producción de papa y la calidad del tubérculo mientras se reduce el uso del agua.

Keywords Specific gravity · Tuber bulking · Tuber initiation · Water stress · Yield losses

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Introduction

In arid regions, drought due to limited water resources and low rainfall is a challenge to vegetable production. Potato (*Solanum tuberosum* L.) crop production in such areas depends, to a great extent, on water supplied through irrigation systems to ensure high marketable yield and good tuber quality (Stark et al. 2013). The sensitivity of crops to soil moisture shortage depends on their growth stage (Alva 2008). Potato plants are sensitive to water stress chiefly during the most sensitive growth stage (tuber bulking), when water shortage may cause reduction in tuber yield, grade and quality (Karam et al. 2005; Shock et al. 2007). To overcome the effects of water stress, it is crucial to adopt appropriate agricultural practices and to optimally meet water requirements at growth stages sensitive to water stress (Ali 2014). Wright and J.C.

Stark (1990) reported that some water stress can be tolerated during early vegetative growth and late tuber bulking stages. Plants are mainly sensitive to drought during tuber initiation, when it can reduce tuber number and lower yield (Havaerkort et al. 1990; Thornton 2002). To ensure high productivity, Steyn et al. (2007) suggested that water stress should be avoided from tuber initiation until tuber bulking. Thus, applying sufficient irrigation at the right physiological stage has become a challenge for potato farmers. Scheduling water application is essential to ensure the most efficient use of drip irrigation systems, as excessive irrigation decreases yield, while insufficient irrigation leads to water stress and reduces production (Shock et al. 2007; Khakbazan et al. 2011; Ayas 2013).

Organic fertilizer, such as humic substances (HS), plays a vital role in agricultural systems through its benefits on both plant and soil. It enhances plant growth and development, improves soil properties, and increases root penetration within the soil (Sarhan et al. 2011; Moghadam et al. 2014). Moreover, organic fertilizer can increase the ability of roots to capture moisture, which increases water use efficiency (WUE), particularly in sandy soils. Humic acid (HA) is considered a medium for delivering essential nutrients to improve plant growth and increase yield (Sanli et al. 2013). In addition, studies of the positive effects of HA on plant development have demonstrated the significance of optimum mineral supply separately from nutrition (Dursun et al. 2002). Many studies have indicated that HA application can increase potato yield and improve tuber quality (e.g. Mahmoud and Hafez 2010; Sanli et al. 2013; Abu-Zinada and Sekh-Eleid 2015). The stimulatory effects of HA on plant growth, yield, and nutrient uptake have been studied on several economic crops, including potato. However, studies on the potential of HA to enhance drought tolerance are still in progress, and more investigation is required (Calvo et al. 2014).

The interacting factors of water stress imposed at different growth stages together with the application of HA treatment can affect the amount of water available to the growing crop, especially under arid conditions. Hence, this study was conducted to: (a) determine the effects of water regimes applied at various growth stages on plant growth, tuber development, tuber quality, and WUE of potato and (b) evaluate the ability of HA application to increase the potato plants tolerance to water stress.

Materials and Methods

Two field experiments were carried out at the Agricultural Research and Experimental Station, Dirab, Riyadh, Saudi Arabia (24° 39′ N, 46° 44′ E). The potato cultivar Hermes was chosen since it is considered as a medium-maturing plant and is a commonly used cultivar in the potato industry (Ayas and Korukçu 2010).

Soil and Irrigation Water Analyses

Before the experiment, physical and chemical properties of the soil were determined from samples collected from the 30 cm depth. Chemical properties of the irrigation water were also estimated. The soil texture was sand (80.69 % sand, 6.85 % coarse sand, 5.97 % silt and 6.49 % clay) with an average pH of 8.1, organic matter content of 0.16 % and electric conductance (EC) of 1.72 dS m^{-1}. Available soil N, P and K were 6.10, 9.68 and 138.81 mg kg^{-1}, respectively (Chapman and Pratt 1978). For the irrigation water, EC = 1.24 dS m^{-1}; ion content: Na = 3.69, Ca = 2.14, Mg = 1.19, HCO_3 = 2.58, Cl = 3.69, SO_4 = 0.97 meq l^{-1}.

Irrigation Water Regimes

Potato seed pieces were sown on 25 Nov. 2011 in the first season and 29 Nov. 2012 in the second season. Seed pieces were irrigated uniformly in all plots with a drip irrigation system in the first 10 day to ensure good establishment. To determine the growth period during which potato plants are most sensitive to water regimes, five irrigation treatments were performed at the following three developmental stages (Steyn et al. 2007):

S1, Vegetative growth, up to 40 day after planting (DAP);
S2, Tuber initiation, from 41 to 74 DAP;
S3, Tuber bulking, from 75 to 110 DAP.

The five irrigation treatments, based on crop evapotranspiration (ETc), were divided across the three developmental stages as follows:

WR1: full irrigation (100 % ETc) without any water restriction at the whole growing period (control)
WR2: 75 % ETc throughout the entire growing period.
WR3: 75 % ETc at S1 and 100 % ETc during S2 and S3.
WR4: 75 % ETc at S2 and 100 % ETc during S1 and S3.
WR5: 75 % ETc at S3 and 100 % ETc during S1 and S2.

Irrigation scheduling was established using "class A" pan evaporation, and total irrigation water supply was estimated based on the following crop coefficients (Kc) equation (Allen et al. 1998): ETc = Eo x Kp x Kc, where

ETc maximum daily crop evapotranspiration in mm.
Eo evaporation from a class A pan in mm.
Kp pan coefficient with ranges between 0.7 and 0.9.
Kc crop coefficient with ranges between o.4 and 1.2 depending on growth stage.

The Kp and Kc were calculated according to Allen et al. (1998) equations.

Total water requirement across all three growing periods (100 day) was 1600 m^3 ha^{-1} for WR1, 1200 for WR2, 1480 for WR3, 1464 for WR4 and 1456 m^3 ha^{-1} for WR5.

Humic Acid Application

Humic Acid 86+6 % (Huma K, Humic Acid 56 %, Fulvic Acid 30 %, Potassium 6 %) in black granule form (Ferzan Liquid Fertilizers, Theriad Energy Company, USA) was added as a soil application at rate of 1.5 g L^{-1}, 30 day after planting potato seed pieces as suggested by Sarhan (2011). HA granules were mixed well in water and sprayed in lines 10 cm beside the plants. Control treatment was sprayed with normal irrigation water.

Experimental Design

The experimental design used was randomized complete blocks arranged in a split plot system. Irrigation treatments were applied to the main plots, replicated four times, and HA treatments were applied to sub-plots within the main plots. Plots were 20 m long and comprised 30 rows spaced 1 m apart with tubers planted every 25 cm. Between all main plots, one row was left empty to eliminate any effects of lateral water movement. Weed control was carried out manually three to four times depending on weed density. All other practices for potato production, such as fertilizer application and pest control, were achieved (Tantowijoyo and van de Fliert 2006).

Vegetative Growth and Yield Traits

At the end of tuber initiation stage (70 DAP), the aerial parts of six plants present in the middle three rows of each plot were cut. Plant height, number of branches per plant, vine fresh and dry weights were measured. At harvest time (110 DAP), six plants from the three inner rows of each plot were harvested and the following traits were measured for ten tubers from each plot: average tuber weight, tuber number and tuber diameter. The remaining plants in the same three rows were harvested to determine the total tuber yield. Harvested potato tubers were classified into different size grades according to weight (G1, less than 80 g; G2, 80–120 g; G3, over 120 g).

Tuber Quality

Six randomly selected tubers from each experimental sub-plot were selected for dry weight and starch content measurements. Tuber dry weight was estimated by sampling 50 g of tissue from these six tubers, finely slicing the samples and drying them in a drying oven at 65 °C for 4 days (Steyn et al. 2007). Starch content was determined following the AOAC method (AOAC 2000). Specific gravity trait was calculated from 2 kg of tubers, weighed in air and water, according to Esendal's (1990) formula as reported by (Sanli et al. 2013):

Specific gravity = weight of tubers in air/ (weight in air – weight in water).

Water Use Efficiency

WUE is described as the tuber yield obtained per unit of water consumed by the potato plants as evapotranspiration (Doorenbos and Pruitt 1977). It was calculated based on the formula used by Reddy and Reddi (2002):

WUE Tuber yield kg ha^{-1}/Water applied through irrigation (m^3 ha^{-1}) during the entire growing season.

Statistical Analysis

Treatment effects were tested by analysis of variance (ANOVA) using SAS for Windows statistical software, version 8.1. A revised least significant difference (LSD) test at the 0.05 probability level was used to measure statistical differences between irrigation levels and HA treatment means (Steel and Torrie 1980).

Results and Discussion

Vegetative Growth Traits

The influence of water stress depends strongly on the stage of plant growth (Alva 2008). Significant differences were found in vegetative growth traits of potato plants under different irrigation regimes. Overall, the control treatment (WR1) gave the highest values of plant height, branch number, and fresh and dry vine weights. The lowest values of these traits were found under treatment WR3 (Table 1). The WR3 treatment indicates that the vegetative growth stage is more sensitive to water stress than other stages. Plant height was affected by water stress; it reached its maximum value under full irrigation earlier than under water stress treatments. Number of branches per plant showed the same tendency as plant height. These results confirm the findings of Alva (2008) and Kahlon and Khera (2015), who found that water stress during the vegetative growth stage causes reduction in leaf area, vine and root expansion, and plant height, as well as delaying canopy development. In earlier growth stages, full irrigation can supply enough water to plants and thus maintain adequate turgor, which improves the development and growth of plant stem and branches (Shiri-e-Janagard et al. 2009). Full irrigation permitted optimum transpiration and faster growth of the aerial parts (Quezada et al. 2011; Khakbazan et al. 2011).

Application of HA further improved vegetative growth traits compared with the control plants (Table 1). HA supplies nutrients for physiological processes in the plant that ultimately enable growth (Sarhan 2011; Rizk et al. 2013). Also, HA

Table 1 Effect of irrigation water treatments and humic acid (HA) applications at different growth stages on vegetative growth traits of potato (Hermes cv.) during 2011/2012 and 2012/2013 years. Means are given for each treatment group; values in the same column followed by the same letter are not significantly different at $p = 0.05$

Growing seasons	First season (2011/2012)				Second season (2012/2013)			
Vegetative growth traits Exp. treatments	Plant height (cm)	Number of branches plant^{-1}	Vine fresh weight (g)	Vine dry weight (g)	Plant height (cm)	Number of branches plant^{-1}	Vine fresh weight (g)	Vine dry weight (g)
(a) Water treatments								
WR1 (control)	72.67 a	5.68 a	613.85 a	70.13 a	74.30 a	5.55 a	622.28 a	71.78 a
WR2	67.03 c	5.11 c	531.00 b	65.32 c	68.48 c	5.25 c	536.62 b	66.72 c
WR3	56.28 e	4.52 e	442.10 e	59.87 e	58.15 e	4.65 e	452.50 e	61.73 e
WR4	63.77 d	4.85 d	447.43 d	62.23 d	65.83 d	5.00 d	504.77 d	63.60 d
WR5	68.58 b	5.53 b	519.80 c	65.70 b	71.42 b	5.47 b	526.95 c	67.37 b
(b) Humic acid (HA)								
HA	67.41 a	5.26 a	530.95 a	67.74 a	69.53 a	5.31 a	539.25 a	69.21 a
No HA	63.92 b	5.06 b	508.72 b	61.56 b	65.75 b	5.05 b	517.97 b	63.27 b

increases root respiration and penetration in soil, enhancing growth of the root system, shoot growth and other vegetative traits, which improves the response of plant to abiotic stress (Garcia et al. 2008; Sarhan et al. 2011).

Tuber Yield and Yield Components

The highest number of tubers per plant was obtained in the control treatment (WR1) while the smallest number occurred in treatment WR4, followed by treatment WR3 (Table 2). These results are in agreement with Alva (2008) who reported that the number of tubers per plant decreases due to water stress at the tuber initiation stage, particularly in certain potato varieties. Water stress during the vegetative growth stage causes a reduction in the number of tubers, which may then result in fewer but larger tubers at harvest (King et al. 2003). Under the control treatment (WR1), large (G3) and medium-sized (G2) potatoes accounted for 38.2–40.2 and 37.7–37.9 % of total tuber production, respectively. Walworth and Carling (2002) suggested that full irrigation increases the number of large tubers. When irrigation water supply before and at tuber initiation is sufficient, the number of tubers per plant increases (Shock et al. 1992), while after tuber initiation, water supply increases tuber size (Eldredge et al. 1996; Shock et al. 1998). The present results were in accordance with Sharafzadeh et al. (2011) who found that under a sufficient water supply, the frequency of undersized tubers decreased and the frequency of marketable tubers increased. In contrast, WR2 generated the largest percentage (27.7–29.5 %) of small potatoes (G1) per total tuber production. Thus, tuber size decreased under continuous water stress treatment (WR2) in comparison with other water treatments (Table 2). These results show that tuber size in the Hermes cultivar decreases with increased water stress, chiefly during the tuber initiation stage (WR4). In a comparison of several potato cultivars, Stark et al. (2013) concluded that the tuber yield was maximized when plants were supplied with full irrigation up to mid-bulking, followed by a gradual reduction in water supply. Kahlon and Khera (2015) demonstrated that water stress during tuber initiation can considerably reduce tuber yield. However, Fabeiro et al. (2001) and Karam et al. (2014) reported that the greatest reductions in tuber yield occurred when plants were exposed to water stress at the end of the season or during tuber bulking. Assessment among water regime treatments showed that, water stress at tuber bulking stage (WR5) increased tuber weights in the biggest size grade (G3) and yielded more tubers compared with other water regime treatments (Table 2). More tubers per plant and a higher yield of large tubers increased productivity of potato, which was most marked in the control (WR1) followed by treatment WR5. Shiri-e-Janagard et al. (2009) showed that increasing the amount of irrigation increased the number of large tubers and their average fresh weight, ultimately increasing potato yield. Total yield was greatly reduced when water stress was imposed at the tuber initiation stage (WR4, treatment) (Table 2). This suggests that the tuber initiation stage is sensitive to water stress. Walworth and Carling (2002) indicated that both emergence and tuberization (sink strength) are critical periods where water stress most influences final tuber yield. However, Qin et al. (2013) reported that water stress during tuber initiation and in early-bulking stages decreases potato yield due to more frequent tuber malformations.

Application of HA had a positive influence on the number of tubers per plant, increasing the production of small, medium and large tubers (less than 80; 80–120 and over 120 g). This resulted in the highest total yield compared to the control treatment. HA treatment increased the number of large (G3, over 120 g) tubers by 47.1–56.0 % over the control treatment

Table 2 Effect of irrigation water treatments and HA applications at different growth stages on different aspects of potato yield (Hermes cv.) during 2011/2012 and 2012/2013 years. Means are given for each treatment group; values in the same column followed by the same letter are not significantly different at $p=0.05$

Growing seasons	First season (2011/2012)					Second season (2012/2013)				
		Fresh tuber yield (t ha^{-1})					Fresh tuber yield (t ha^{-1})			
Tuber yield traits Exp. treatments	Tuber number plant^{-1}	G1 (<80 g) (t ha^{-1})	G2 (80–120 g) (t ha^{-1})	G3 (>120 g) (t ha^{-1})	Total tuber yield(t ha^{-1})	Tuber number plant^{-1}	G1 (<80 g) (t ha^{-1})	G2 (80–120 g) (t ha^{-1})	G3 (>120 g) (t ha^{-1})	Total tuber yield(t ha^{-1})
(a) Water treatments										
WR1 (control)	8.00 a	9.94 d	17.19 a	18.21 a	45.34 a	7.90a	10.83 d	16.94 a	17.15 a	44.92 a
WR2	7.27 b	12.54 a	16.33 b	10.42 c	39.29 c	7.35b	13.26 a	15.50 b	11.20 c	39.95 c
WR3	5.47 c	11.55 b	11.95 d	2.88 e	26.38 d	5.57c	12.14 b	12.60 d	3.34 e	28.09 d
WR4	4.58 d	9.03 e	10.07 e	4.80 d	23.90 e	4.72d	9.76 e	10.93 e	4.39 d	25.07 e
WR5	7.22 b	10.96 c	15.73 c	13.89 b	40.58 b	7.30b	11.63 c	14.95 c	14.44 b	41.02 b
(b) Humic acid (HA)										
HA	6.64 a	11.25 a	14.80 a	12.24 a	38.28 a	6.73 a	11.93 a	14.21 a	12.03 a	38.16 a
No HA	6.37 b	10.36 b	13.71 b	7.84 b	31.91 b	6.41 b	11.12 b	14.16 a	8.18 b	33.46 b

(Table 2). This finding agrees with the results of Hopkins and Stark (2003) who reported that the main effect of HA treatment on U.S. No. 1 potato yield was mediated by the increase in tuber size. The increase in all components of potato tuber yield may be attributed to HA's improving vegetative growth traits (Table 1). Sarhan (2011) reported that the increase in potato yield (cultivar Desiree) may be brought about by the influence of HA on the shoot system rather than an increase in the number and weight of tubers, which contributed to the increase in total tuber yield. Furthermore, Verlinden et al. (2009) and Selim et al. (2009) found that HA application increased the number of tubers and yield. The obtained results revealed that HA application might be increased organic matter per the soil, although it was limited (0.16 %) in the planting soil at the beginning of experiment. Similar results were reported by Sajid et al. (2012) for onion crop since HA applications led to significant increase in soil organic matter. In general, HA application increases soil fertility, soil moisture content and provides important nutrients for better plant growth and crop yield (Sanli et al. 2013).

Potato Tuber Quality Traits

Drought is one of the most limiting conditions that can influence tuber quality. More severe water stress is associated with reductions in tuber weight, size, and yield (Bethke et al. 2009). In this study, tuber fresh weight was the greatest under the control (WR1) treatment (Table 3). Belanger et al. (2002) stated that there is a 40 % reduction in tubers bulking rate under water stress than normal irrigation treatment, caused a decrease in tuber average weight. Similarly, the WR1 gave the largest tuber diameter, although it was not significantly different from WR5. In addition, WR5 gave higher tuber dry weight and starch content, while water stress during the entire growth period (WR2) gave the highest tuber specific gravity (Table 3). In contrast, the smallest tuber diameter occurred in treatment WR4. Thus, tuber size was affected when water stress was imposed at the tuber initiation stage (S2). These results agree with Hassan et al. (2002) who concluded that the stolonization and tuberization stages were more sensitive to water stress than the bulking stage. Increasing specific gravity at WR2 treatment supports the results of Stark et al. (2013) who reported that as the soil dries, transpiration surpasses root water uptake for a period of time as the plants regulate to developing drought, thereby decreasing water content of tuber and increasing specific gravity. Starch content increased markedly with water stress in general, chiefly in WR5 over WR1 (average 15.3–17.3 % over WR1). This suggests that water stress at the tuber bulking stage increased starch content more than in other treatments (Table 3). Hence, temporary periods of water stress should be prevented in order to enhance the amount and quality of tuber yield (Sharafzadeh et al. 2011).

Table 3 Effect of irrigation water treatments and HA applications at different growth stages on aspects of weight, size and quality of potato tubers (Hermes cv.) during 2011/2012 and 2012/2013 years. Means are given for each treatment group; values in the same column followed by the same letter are not significantly different at $p = 0.05$

Growing seasons	First season (2011/2012)					Second season (2012/2013)				
Tuber traits Exp. treatments	Tuber fresh weight (g)	Tuber diameter (cm)	Tuber dry weight (%)	Specific gravity	Tuber starch (%)	Tuber fresh weight (g)	Tuber diameter (cm)	Tuber dry weight (%)	Specific gravity	Tuber starch (%)
(a) Water treatments										
WR1 (control)	141.65 a	6.62 a	24.50 d	1.02 e	17.28 e	142.08 a	6.77 a	24.25 c	1.05 e	17.22 e
WR2	135.13 c	6.37 b	25.60 b	1.14 a	18.28 d	135.85 c	6.52 b	25.40 a	1.14 a	18.35 d
WR3	120.60 e	6.22 c	22.98 e	1.08 d	18.67 c	126.12 e	6.33 c	23.23 d	1.09 d	18.80 c
WR4	130.32 d	6.13 d	24.90 c	1.09 c	19.03 b	132.83 d	6.25 d	24.63 b	1.10 c	19.22 b
WR5	140.48 b	6.57 a	25.97 a	1.11 b	19.93 a	140.38 b	6.75 a	25.55 a	1.12 b	20.20 a
(b) Humic acid (HA)										
HA	135.44 a	6.59 a	24.49 b	1.21 a	18.85 a	137.90 a	6.71 a	24.42 b	1.21 a	18.96 a
No HA	131.83 b	6.17 b	25.09 a	1.09 b	18.43 b	133.01 b	6.33 b	24.81 a	1.10 b	18.55 b

HA increased tuber fresh weight, tuber diameter, specific gravity, and starch content. However, it decreased tuber dry weight (Table 3). These results are similar to the findings of Ghannad et al. (2014), who reported that applying HA increased specific gravity and decreased dry weight of potato tubers in comparison with a control treatment. Moreover, Mahmoud and Hafez (2010) found that the fresh weight, size, and quality of potato tubers significantly increased with increased levels of HA application. Selim et al. (2009) observed that application of HA through a drip irrigation system improved starch and protein content as well as other quality traits (N, P and K concentrations) of potato tuber tissues. These improvements may be due to the vital role of HA as a soil conditioner, maintaining the supply of soil nutrients, increasing soil holding capacity and improving moisture retention (Piccolo et al. 1996; El Dsouky and El Sagan 2015).

Water Use Efficiencies (WUE)

Generally, potatoes need considerable amounts of water during the growing season (Khakbazan et al. 2011). Comparisons among mean values of the various water regime treatments indicated that WR2 had the highest mean value of WUE, followed by WR1 and WR5, while the lowest mean value was recorded under WR4 (Fig. 1). The transient stress treatments during vegetative growth and tuber initiation stages reduced WUE and were associated with the lowest tuber yield (Table 2). The effect of water regimes on WUE can be attributed to the level of water stress during different growth stages. Under mild water stress, transpiration decreases more than photosynthesis during slight stomata closure and, consequently, WUE increases (Cantore et al. 2014). Miller and Martin (1987) and Alva (2008) exhibited that sufficient water availability during most of the plant growing period is crucial for maintaining optimal crop production in potato. Even short periods of water stress negatively affect tuber production. Carli et al. (2014) found that decreasing water supply after the tuberization stage only slightly affected tuber yield.

HA application significantly increased WUE compared with the control treatment (Fig. 2). A similar result was attained by Sadeghi-Shoae et al. (2013) who found that the highest WUE in sugar beet was obtained via the application of HA along with irrigation. The role of HA in increasing WUE probably results from its role in advancing root development and penetration, which increases the ability of plants to absorb water from the soil (Feleafel and Mirdad 2014). Recently, Abu-Zinada and Sekh-Eleid (2015) indicated that humic substances like HA have capability to capture more moisture content that will increase WUE in the sandy soil.

Interaction Effect of Irrigation Treatment and HA Application

The interactions between water regime and HA application had a significant influence on vegetative growth traits. The

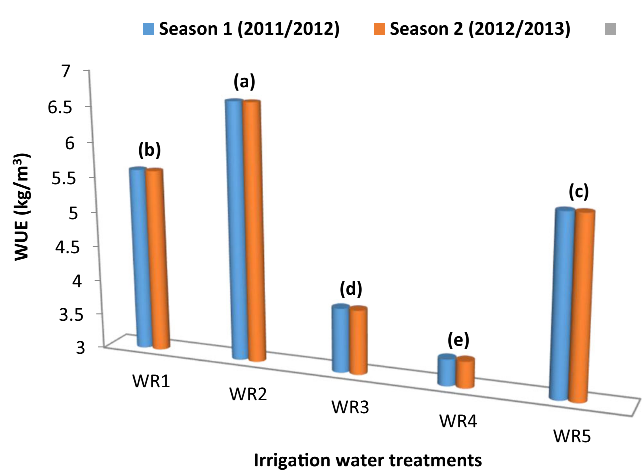

Fig. 1 Effect of irrigation water treatments at different plant growth stages on WUE of potato plants during the 2011/2012 and 2012/2013 growing seasons

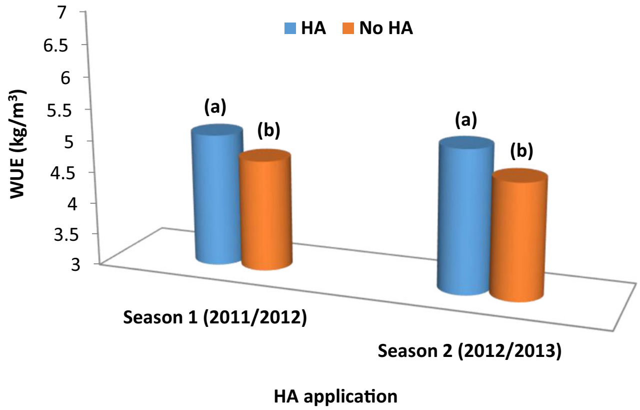

Fig. 2 Effect of HA on WUE of potato plants during the 2011/2012 and 2012/2013 growing seasons

tallest plant, the highest number of branches and the heaviest vine dry weight were observed under WR1 with HA, followed by WR5 with HA. However, the heaviest vine fresh weight was obtained under WR1 with and without HA treatments. Based on the vegetative growth traits studied here, vegetative growth stage is being the most sensitive to water stress than other two stages. WR3 showed the lowest values in all growth traits (Table 4). The increment in plant height and branch number of potato was due to HA nutrients supplied with the availability of full water content. These nutrients involve in plant bioactivities and encourage induction of plant growth (Abdel-Mawgoud et al. 2007). Such increment in vegetative growth may be owing to the enhancing influence of HA on the availability of nutrients and the role of K element in plant nutrition which in turn resulted in increased vegetative growth of potato plants (Mahmoud and Hafez 2010; Abu-Zinada and Sekh-Eleid 2015).

Water regime and HA treatment also showed significant interacting effects on the fresh weight, number and specific gravity of tubers as well as total yield (Table 5). The highest tuber weight, number, and total yield were observed under WR1 with HA, followed by WR5 with HA. This outcome supports the findings of Doorenbos and Kassam (1979) who reported that tuber initiation is the stage most sensitive to water stress, while tuber bulking is the least sensitive. In contrast, Fabeiro et al. (2001) and Karam et al. (2014) found tuber bulking to be the stage most sensitive to water stress. The recent study of Pavlista (2015) revealed the poorest potato plant growth and the lowest tuber yield were obtained when the amount of water decreased by half from tuber initiation through to early tuber bulking stage (early log phase of tuber growth), from 2 to 8 weeks after tuber emergence.

Specific gravity, which is an important quality trait in relation to the processing of tubers (Yuan et al. 2003), was influenced by water treatments. In this study, the highest specific gravity (1.14–1.15) was recorded under WR2 with HA, while WR1 with HA gave the lowest specific gravity (1.01–1.05). This finding supports the results of Gunel and Karadogan (1998) and Cantore et al. (2014), who found that specific gravity decreased with more frequent irrigation at tuber bulking stage, which was related to a higher moisture content of the tuber tissues. This study detected a relatively higher specific gravity (1.14–1.15) in the Hermes potato cultivar (Table 5), which is a trait favored by the industry. Somsen et al. (2004) suggested a specific gravity of 1.075 and above as suitable for the production of French fries.

WUE was also influenced by irrigation water levels, particularly in combination with HA application. Water stress during all growth periods (WR2) with HA gave the highest WUE, which was due to lower water consumption. In general,

Table 4 Interaction effects of irrigation water treatments and HA application at different growth stages on vegetative growth (plant height, number of branches plant^{-1}, and vine fresh and vine dry weights) in the potato (Hermes cv.) during 2011/2012 and 2012/2013 years. Means are given for each treatment group; values in the same column followed by the same letter are not significantly different at $p = 0.05$

Experimental treatments		First season (2011/2012)				Second season (2012/2013)			
Water treatments	Humic acid (HA) application	Plant height (cm)	Number of branches plant^{-1}	Vine fresh weight (g)	Vine dry weight (g)	Plant height (cm)	Number of branches plant^{-1}	Vine fresh weight (g)	Vine dry weight (g)
WR1 (control)	HA	73.50 a	5.70 a	630.77 a	73.17 a	75.96 a	5.63 a	641.50 a	73.70 a
	No HA	70.03 c	5.43 c	596.93 b	67.10 d	72.63 c	5.43 c	602.91 b	68.00 d
WR2	HA	68.57 c	5.43 c	542.50 c	68.53 c	70.40 d	5.46 c	549.82 c	69.37 c
	No HA	65.50 de	5.17 d	519.50 e	62.10 g	66.57 f	5.03 d	523.44 e	63.07 g
WR3	HA	57.17 g	4.60 f	451.57 i	63.03 f	58.77 h	4.83 f	463.52 i	64.10 f
	No HA	55.40 h	4.43 g	432.63 j	56.70 i	57.53 i	4.47 g	441.50 j	57.63 i
WR4	HA	65.63 d	4.87 e	500.73 g	65.43 e	68.07 e	5.07 d	508.81 g	66.10 e
	No HA	61.90 f	4.83 e	484.13 h	59.03 h	63.60 g	4.93 e	500.73 h	60.00 h
WR5	HA	72.20 b	5.63 b	529.20 d	69.53 b	74.43 b	5.53 b	532.60 d	69.77 b
	No HA	64.97 e	5.43 c	510.40 f	62.87 f	68.40 e	5.37 c	521.40 f	63.80 f

Table 5 Interaction effects of irrigation water treatments and HA application at different growth stages on aspects of weight, number and quality of tubers as well yield and WUE in the potato (Hermes cv.) during 2011/2012 and 2012/2013 years. Means are given for each treatment group; values in the same column followed by the same letter are not significantly different at $p = 0.05$

Experimental treatments				First season (2011/2012)					Second season (2012/2013)		
Water treatments	HA application	Tuber fresh weight (g)	Tuber no. plant^{-1}	Total tuber yield (t ha^{-1})	Specific gravity	WUE (kg m^{-3})	Tuber fresh weight (g)	Tuber no. plant^{-1}	Total tuber yield (t ha^{-1})	Specific gravity	WUE (kg m^{-3})
WR1 (control)	HA	143.97 a	8.11 a	46.65 a	1.01 h	5.83 c	146.13 a	8.10 a	46.96 a	1.05 h	5.87 c
	No HA	139.33 c	7.50 c	42.03 c	1.04 g	5.50 e	138.03 c	7.60 c	42.88 c	1.06 g	5.36 e
WR2	HA	136.60 e	7.22 d	40.43 d	1.15 a	6.74 a	136.47 e	7.40 d	41.42 d	1.14 a	6.90 a
	No HA	133.67 f	7.20 d	38.14 e	1.12 b	6.36 b	134.23 f	7.13 e	38.48 e	1.13 b	6.41 b
WR3	HA	122.20 i	7.11 e	26.89 f	1.08 f	3.75 g	128.33 i	6.50 f	28.92 f	1.09 f	4.04 g
	No HA	119.00 j	7.00 f	25.86 g	1.08 f	3.61 h	123.90 j	5.43 g	27.26 g	1.10 e	3.81 h
WR4	HA	131.90 g	6.90 g	24.80 h	1.09 e	3.34 i	132.50 g	4.70 h	25.18 h	1.09 f	3.53 i
	No HA	128.73 h	6.51 h	23.00 i	1.10 d	3.10 j	131.17 h	4.47 i	23.96 i	1.11 d	3.23 j
WR5	HA	142.53 b	7.80 b	42.76 b	1.11 c	5.76 d	143.07 b	7.90 b	43.90 b	1.12 c	5.84 d
	No HA	138.43 d	7.20 d	38.39 e	1.11 c	5.17 f	137.70 d	7.03 e	38.74 e	1.12 c	5.22 f

HA application combined with water stress treatments at different growth stages increased potato yield and WUE in comparison with the control treatment (Table 5). With the same water consumption, potato yield was higher when HA was applied. HA has a role in enhancing root growth and retaining soil moisture (Moghadam et al. 2014). On the other hand, WR5 with HA showed increased WUE and total yield compared with WR1 (100 % ETc without HA). HA increases the permeability of plant membranes, promotes the uptake of nutrients, increases water holding capacity, and improves root architecture, which increases stress tolerance (Chen and Aviad 1990; Calvo et al. 2014).

Yield Losses and Water Saving

The interaction results showed clearly that combining irrigation treatments during different growth stages with HA application can enhance yield. Full irrigation (WR1) with HA produced 9.5–11.0 % greater yield than WR1 without HA (Table 6). Sadeghi-Shoae et al. (2013) recorded a 25 % increase in the root yield of sugar beet under HA application with full irrigation. In this study, the increased tuber yield (+1.0 to +1.7 %) under WR5 with HA while saving 9.0 % of applied water confirmed the study of Stark et al. (2013), who concluded that providing full irrigation through the mid-

Table 6 Yield losses (%) and water saving (%) due to the interaction between irrigation water treatments and HA application during the years of 2011/2012 and 2012/2013

Interaction treatments	First season (2011/2012)					Second season (2012/2013)				
	Total yield (t ha^{-1})	Yield ratio to control treatment (%)	Yield potential gain/loss (%)	Water ratio to control treatment (%)	Water saving (%)	Total yield (t ha^{-1})	Yield ratio to control treatment (%)	Yield potential gain/loss (%)	Water ratio to control treatment (%)	Water saving (%)
WR1 + (HA)	46.65	111	+11.0	100	0.0	46.96	109.5	+9.5	100	0.0
WR1 + (No HA)	42.03	100	0.0	100	0.0	42.88	100	0.0	100	0.0
WR2 + (HA)	40.43	96.2	−3.8	75	25.0	41.42	96.6	−3.4	75	25.0
WR2 + (No HA)	38.14	90.7	−9.3	75	25.0	38.48	89.7	−10.3	75	25.0
WR3 + (HA)	26.89	64.0	−36.0	92.5	7.5	28.92	67.4	−32.6	92.5	7.5
WR3 + (No HA)	25.86	61.5	−38.5	92.5	7.5	27.26	63.5	−37.5	92.5	7.5
WR4 + (HA)	24.80	59.0	−41.0	91.5	8.5	26.18	61.1	−38.9	91.5	8.5
WR4 + (No HA)	23.00	54.7	−45.3	91.5	8.5	23.96	55.8	−44.2	91.5	8.5
WR5 + (HA)	42.67	101.7	+1.7	91.0	9.0	43.30	101	+1.0	91.0	9.0
WR5 + (No HA)	38.39	91.3	−8.7	91.0	9.0	38.74	90.3	−9.7	91.0	9.0

bulking stage, followed by a slow reduction in irrigation was the best strategy for reducing yield losses under insufficient water availability.

Continuous water stress during entire growth periods (WR2) with HA resulted in small yield losses (−3.4 to −3.8 %) while saving 25 % of irrigation water (Table 6). These findings might indicate a role for HA in reducing yield losses and saving irrigation water under conditions of water stress. This might allow resulting yield reduction to be minimized while maximizing the benefits of using the saved water to irrigate other vegetable crops (Kirnak et al. 2002). Application of HA to potato plants provides nourishment and improves their ability to absorb more water, which increases the water holding capacity of the soil and makes the plants more resistant to drought stress (Sajid et al. 2012). As a result, HA has a positive effect on potato development and helps plants tolerate abiotic stress conditions (water stress), thereby reducing yield losses.

Conclusion

Water regime during the tuber bulking stage, accompanied by application of 1.5 g L^{-1} HA at the vegetative growth stage, enhanced tuber yield of potato (Hermes cultivar), while saving 9.0 % of irrigation water compared to the control treatment or other water regime treatments at different growth stages. This result indicates a positive effect of HA on potato tuber development and water stress tolerance, which can mitigate yield losses. A water shortage of 25 % at the bulking stage with HA application during vegetative growth could be adopted to improve production while saving irrigation water in potato cultivation. This conclusion is particularly valuable in arid regions, where water shortage is an increasing concern and water costs are continually rising.

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