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IMPACT OF ADVANCED AND DELAYED IRRIGATION PRACTICES ON PHYSICO-CHEMICAL ATTRIBUTES OF POTATO TUBERS UNDER BED SOWING

M. S. Waqas[1, *], M. J. M. Cheema[2], S. Hussain[3, 4], A. Daccache[4], M. K. Ullah[5], M. M. Iqbal[6] and H. Hussain[7, 8]

[1]Soil Conservation Group, Agriculture Department (Field Wing), Government of the Punjab, Rawalpindi 46000, Pakistan
[2]Faculty of Agricultural Engineering and Technology, Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi 46000, Pakistan
[3]Department of Irrigation and Drainage, University of Agriculture, Faisalabad 38040, Pakistan
[4]Department of Biological and Agricultural Engineering, University of California, Davis CA 95616, USA
[5]Civil Engineering Department, The University of Lahore, Lahore 54000, Pakistan
[6]Water Management Training Institute (WMTI), Agriculture Department, Government of the Punjab, Lahore 54000, Pakistan
[7]Government Graduate College Khurrianwala, Faisalabad 38000, Pakistan
[8]Department of Chemistry, Quaid-I-Azam University, Islamabad 45320, Pakistan
*Corresponding Author's E-mail: sohailwaqasrana@gmail.com

ABSTRACT

The wise use of water resources is the dire need of the day due to the alarming situation of water crisis. Management Allowed Depletion (MAD) level irrigation technique is used to enhance crop yield as well as the precise use of water. The present study was designed to investigate the optimum MAD level (when to irrigate) at which tuber yield and quality did not deteriorate significantly. Four different MAD levels were scheduled i.e., irrigation applied when MAD_0 = 0%, MAD_{20} = 20%, MAD_{35} = 35%, and MAD_{50} = 50% of available soil water depleted from the soil at Water Management Research Center, University of Agriculture, Faisalabad-Pakistan during the two successive winter growing seasons (2014-15 and 2015-16). Data of different physico-chemical properties and yield of potato tubers were gathered under the Randomized Complete Block Design (RCBD) and set into standard statistical techniques. Results revealed that physical parameters (i.e., length, thickness, diameter, weight, and actual volume) of potato tubers were significantly affected by the different MAD levels, while MAD_{35} was at par with other irrigation schedules. Different MAD levels didn't show significant effects on some of the physico-chemical properties (i.e., particle density, porosity, specific gravity, tuber starch content, and total soluble solids) of potato tubers, and revealed that these traits are entirely genetic based. While tuber size percentage and yield are significantly affected by the different MAD levels. The maximum yield (i.e., 15.52, 16.76 in tons acre^{-1}) and crop water productivity (i.e., 14.19 and 14.64 in kg m^{-3}) were also observed at MAD_{35} during both years. In nutshell, results revealed that both advanced and delayed irrigation practices severely affect the physical parameters, yield as well as to some extent physico-chemical traits of potato tubers. Therefore, 35% MAD level schedule is the optimum one and recommended for potato cultivation under bed sowing.

Keywords: Drip irrigation; Management allowed depletion; Horticultural crops; Irrigation scheduling; Starch content; Specific gravity.

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INTRODUCTION

Water shortage and availability of fresh drinking water is the burning issue worldwide that consequently ranked Pakistan at sixth position in the list of water scarce countries (Cheema *et al.* 2014; Dalias *et al.* 2019; Nabi *et al.* 2019). Moisture stress condition in the growing season is very vulnerable to crop productivity (Farahani *et al.* 2009; Rahdari & Hoseini 2012). Pakistan has the largest irrigation network and about 70% of population is directly or indirectly associated with agriculture (Khan *et al.* 2020). On average, agriculture sector accounts for 70% utilization of global freshwater (FAO 2017). Keeping in view the water scarcity conditions, its importance, requirements according to increasing trend of population, and least access to freshwater, there is dire need of the day to use available water supplies efficiently.

Irrigation and sowing methods also play an important role in the accessibility of water and nutrients to the crop (Waqas *et al.* 2018a). The number of irrigation techniques are available i.e. flood irrigation, border irrigation, furrow irrigation, High Efficiency Irrigation System (HEIS) and each method has its own efficiency level ranging from 40% to 90% (Ati *et al.* 2012). HEIS includes sprinkler and drip irrigation systems having 65 to 75% and 80 to 90% irrigation efficiency respectively (Jägermeyr *et al.* 2015; Hussain *et al.* 2018). Therefore, sustainable use of water resources can only be done through HEIS. Asif *et al.* (2015) design and evaluate a drip irrigation system for the citrus orchard and found more than 80% water application uniformity. Hou *et al.* (2010) also worked on a drip irrigation system and describes that this is an effective method for gaining high potato yield. Management Allowed Depletion (MAD) level is another water application technique that works on how much and when to irrigate by allowing fixed depletion of water. Previously, several research studies described that crop productivity can be enhanced if MAD level sets accurately (Erdem *et al.* 2006; Eiasu *et al.* 2007; Kaminski *et al.* 2015; Safdari *et al.* 2018; Waqas *et al.* 2021).

Potato (*Solanum tuberosum* L.) is a very important vegetable and part of daily food worldwide. China is the world's largest producer of potato (Zhang *et al.* 2017) and average yield increases from 13.5 t ha^{-1} to 17.1 t ha^{-1} (Yang *et al.* 2016). Production of potato in China was 99.21 million tons while Pakistan produced 4.14 million tons during 2017 that is very low as compared to other potato producing countries (FAO 2019). Potato is a balanced food having high-energy protein, vitamins, nutrients, and minerals (Pino *et al.* 2007) and yields more dry matter and protein. Likewise, Öztürk *et al.* (2011) found the concentrations of heavy metals in the order Fe>Zn>Mn>Cu>Ni>Pb>Cd from the sixteen potato cultivars in Turkey. Moreover, recent studies have shown that potato crop is sensitive to nutrients and irrigation water (Deblonde & Ledent 2001; Kumar *et al.* 2007). While the quality of potato tubers can directly affect by a deficit supply of water and nutrients (Waqas *et al.* 2018b). Pakistan is having a supply-based irrigation system instead of a demand-based irrigation system. With a limited supply of water, potato crop can face moisture stress and crop health may go under stressed conditions, which ultimately affects the tuber quality and quantity (Devaux *et al.* 2010). Potato crop can go under stress conditions due to under, over, and non-uniform application of insecticides/pesticides. Therefore, Hussain *et al.* (2019) suggested that uniform application of agro-chemical spraying can be done with a UAV spraying system. Moreover, different potato planting methods are practiced worldwide, while in Pakistan ridge planting with furrow irrigation method mostly adopted. Sood & Singh (2010) and Qasim *et al.* (2013) found higher yield and Water Use Efficiency (WUE) by planting potatoes on beds. Higher yield with improved quality of potato tubers is greatly concerned with growers while besides these factors using the optimum irrigation water is also an important for sustainable use of water.

Physical parameters of agricultural produces play an important role in the designing of grading, handling, packaging systems, and in other areas of processing (Dalvand 2011; Teye & Abano 2012; Tsegaye 2019). Physical parameters of potato tubers (i.e., length, thickness, diameter, weight, surface area, shape factor or sphericity, and volume) like those of other agricultural products are important for practical usage. These are essential for the designing of harvesting, handling, and sorting machinery. Additionally, these parameters are noteworthy in the forecasting of surface required when spraying chemicals, during heating, cooling practices, and in other areas of industrial processing (Mohsenin 1986; Ismail 1988). Physical appearance is also a primary benchmark during the purchasing process (Kays 1991). Moreover, tuber size and shape are very important characteristics when potato tubers are marketed for industrial processing (Haase *et al.* 2007; Abong *et al.* 2010). While the shape of the potato tuber is a morphological feature that exhibits variation ranging from compressed to long (Custers 2015).

Physico-chemical properties (i.e., particle density, bulk density, porosity, specific gravity, tuber dry matter percentage, tuber starch content, and total soluble solids) of potato tubers also play an important role in the processing industry. The quality of potato tuber is an important trait of potato production and is mostly affected by quality parameters like dry matter, sugar content, and other physical parameters (Abbas *et al.* 2011). In grading processes density of product are worth concerning. Potato tubers having more specific gravity are ideal for chips but less resistant to bruising while low gravity tubers are chosen for the canning process (Smith 1977), while a sufficient amount of dry matter in potato tuber is required for dehydrated products. It is, therefore, necessary to determine the physio-chemical quality parameters of potato tubers. Growers must keep in mind that both consumers and industry are interested in quality, moreover there is a need to fulfill the processing requirements.

The current scenario of water scarcity has now limited the crop production, and put a major challenge for the agricultural sector *viz.* ''*more crop per drop*''. The Crop Water Productivity (CWP) in kg m^{-3} is an indicator to address this challenge, which is generally expressed as a ratio of crop yield (kg ha^{-1}) as an output to the irrigation water used (m^3 ha^{-1}) as an input to produce the crop (Waqas *et al.* 2021). The CWP plays a pivotal role in sustainable agricultural development and can be improved by adopting water-saving irrigation approaches. Irrigation methods, that contribute in improving CWP should be adopted to save the scarce water resources and a significant increase in crop production (Zhang *et al.* 2008; Ahmadi *et al*. 2014). Waqas *et al.* (2021) reported that the MAD level irrigation technique is the promising one in saving irrigation water without a significant decline in potato yield. Moreover, different research studies also reported that CWP increases under deficit irrigation strategies, compared to full irrigation (Fan *et al.* 2005; Demelash 2013).

Several research studies have been carried out to evaluate the physio-morphological, chemical compositions, and other quality traits of potato tubers influenced by different irrigation intervals, potato genotypes, cultivar and plant spacing, different levels of NPK, potassium management, different nitrogen, and phosphorus rates in Pakistan and across the globe (Tabatabaeefar 2002; Öztürk *et al.* 2010; Abbas *et al.* 2011; Dalvand 2011; Naz *et al.* 2011; Abbas *et al.* 2012; Pervez *et al.* 2013; Tsegaye 2019). While, there has been limited work in the literature to disclose the effects of different MAD levels on physical parameters and physico-chemical properties of potato tubers under bed sowing, making this study novel and beneficial for potato farmers along with policy-makers.

Keeping in view the importance of potato, based on the literature discussed above, increasing demand of consumers, and foreign importers. A prominent cultivar of potato (cv. Desiree) was selected. The present research work was undertaken to explore the effects of different irrigation schedules (MAD levels) through drip system under raised bed sowing pattern on physical parameters and physico-chemical properties of potato tubers. The core objective of this study was to assess an accurate MAD level that not only improves quality traits but also gives higher yields with higher financial returns to the potato growers. It is expected that the findings of the present study will deliver superior guidelines to the farmers, which ultimately help in improving their living standards due to high crop returns.

MATERIALS AND METHODS

Experimental site: Research trials on potato crop were carried out during the two successive winter growing seasons of 2014-15 and 2015-16 at Water Management Research Center, University of Agriculture, Faisalabad-Pakistan (WMRC-UAF). The climate of the location is semi-arid with a relatively flat topography. The average annual rainfall is about 784 millimeters and almost half of the yearly rainfall receives in the monsoon period (i.e. July and August). Three samples of soil were taken randomly from different locations of the experimental site and analyzed to access the physico-chemical parameters of soil. Field capacity (19.1%), wilting point (8.4%), and bulk density (1.55g/cm^3) were observed and other soil properties of the experimental site are listed in Table 1.

Table 1. Showing pre-sowing physico-chemical properties of soil at experimental site (WMRC-UAF) during 2014-15 and 2015-16.

Parameters	pH	EC	TSS	Organic Matter	Nitrogen	Phosphorus	Potassium	Textural Class
Year	----	(dS m^{-1})	(me L^{-1})	----- (%) -----		----- (ppm) -----		----
2014-15	8.0	1.32	13.80	0.49	0.02	7.20	80	Sandy loam
2015-16	8.2	1.40	14.96	0.42	0.02	7.85	78	Sandy loam

The source of irrigation was groundwater from a skimming tube well. Water samples of the irrigation water source were collected safely and tested in the WMRC-UAF laboratory for quality assurance. Results reveal that irrigation water was marginally fit for irrigation with pH 6.80, EC (dS cm^{-1}) 1.64, TSS (ppm) 1052, Carbonate (me L^{-1}) 0.80, Bicarbonate (me L^{-1}) 5.60, Total hardness (ppm) 288.64, SAR 5.64, and RSC (me L^{-1}) 0.60.

Experimental design and treatments: The research trials were conducted in Randomized Complete Block Design (RCBD) with three replications (Fig. 1). Four MAD level treatments through drip irrigation system under bed sowing pattern were scheduled i.e., irrigation applied when MAD_0 = 0%, MAD_{20} = 20%, MAD_{35} = 35%, and MAD_{50} = 50% of Available Soil Water (ASW) consumed by the crop. Treatments were designed in such a way that when the specific percentage of ASW was consumed by the crop and again refilled the root zone up to the field capacity (0% depletion).

The top and bottom dimensions of beds were 90 cm and 150 cm respectively followed by 60 cm wide furrow (Fig. 2). Each experimental replicated plot was 42 ft. × 50 ft. in dimension comprising of eight beds while there were two rows of potato plants on each bed. A micro-channel of 6 cm was created on beds between the two plant rows to sure the proper availability of water through laterals of the drip irrigation system (Fig. 2). The experimental plots were isolated by 5 ft. wide patches, to avoid surplus merging of inputs and serve as pathways for data gathering and other field activities.

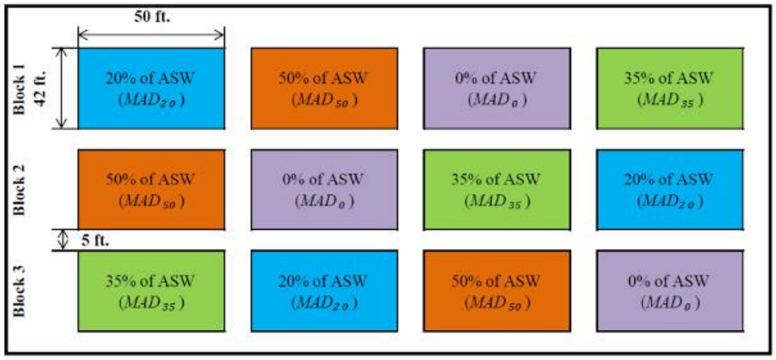

Fig. 1. Systematic experimental layout plan with the randomized complete block design, depicting the percentage of allowed depletion in each treatment.

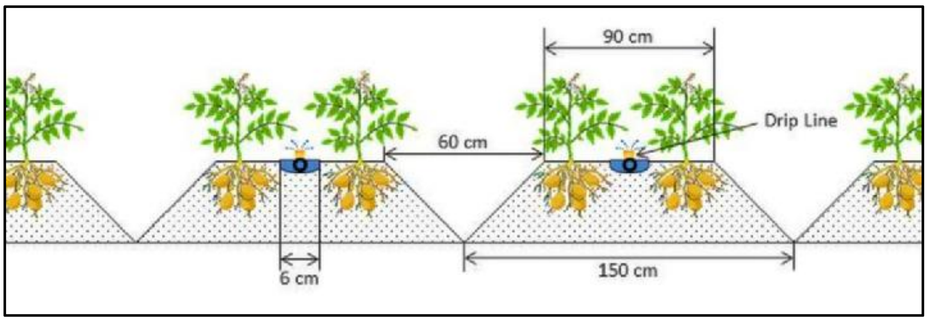

Fig. 2. Showing bed planting geometry with dimensions of designed bed (i.e. top: 90 cm, bottom: 150 cm) with 60 cm wide furrow.

Irrigation scheduling: To discover the performance of drip irrigation system Coefficients of Variation (CV) according to Asif *et al.* (2015) and Emission Uniformity (EU) according to Keller & Karmeli (1974) was determined using the following equations.

$$CV = \frac{\sigma}{q_a} . \qquad [-] \qquad (1)$$

$$EU = 100 \left[1 - 1.27 \frac{c}{\sqrt{n}}\right] \frac{q_m}{q_a} . \qquad [\%] \qquad (2)$$

Where σ is the standard deviation and calculated as follows.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (q_m - q_a)^2}{n}} . \qquad [L\ h^{-1}] \qquad (3)$$

Where CV is the coefficient of variation, n is the number of emitters, q_{min} is the lowest and q_{avg} is the mean flow rate. For this purpose, the catch-can method was followed and the results confirm that the system was working satisfactorily at 16 psi pressure with 0.076 (CV) and 92.44% (EU).

Pre-sowing irrigation (Rauni watering) was applied about 30 days before land preparation and was not included in total irrigation calculations. All the treatments received 5 cm post-sowing irrigation water (Kor watering) for the proper crop establishment. The rest of the irrigations were applied as per the treatment schedule after these common irrigations.

The percentage depletion of ASW in the root zone was assessed according to Martin *et al.* (1990) using the following equation.

$$MAD = 100 \times \frac{1}{n} \sum_{1}^{n} \frac{F_{i} - \theta_i}{F_{i} - P} . \qquad [\%] \qquad (4)$$

Where n, θ_i, FC_i, and PWP are the number of sections of effective root zone depth, soil moisture in i[th] layer (%), moisture content at field capacity (%), and permanent wilting point (%) respectively.

Irrigation requirement in mm was measured using the following formula mentioned in Eq. (5) according to Choudhary (2016).

$$\text{Irrigation Requirement (mm)} = \frac{(F - M)}{1} \times \frac{B_s}{B_w} \times D_r . \qquad [mm] \qquad (5)$$

Where F_c is field capacity (%), M_c is actual gravimetric moisture content (%), BD_{soil} is bulk density (g/cm^3) of soil, BD_{water} is bulk density of water (g/cm^3) and D_{rz} is root zone depth (mm).

Irrigations were applied to each treatment when a fixed MAD level (i.e. threshold moisture content) was attained. For soil moisture measurements, the gravimetric method was performed by taking soil samples from the middle of the two plant rows in each experimental plot and this was done on daily basis in the early morning.

Land preparation and agronomic practices: For land preparation, one-time moldboard plow for inversion of soil followed by two times disc harrow was applied. Thereafter, two times tine cultivator was applied and leveled with the plank. Tractor mounted bed planter was used for making designed beds. After land preparation, disease free potato tuber seeds of "Desiree" cultivar having minimum of 2-3 eyes were planted manually on 19th October, 2014 and 29th October, 2015 during the first and second year respectively by keeping 45 cm distance between the plant rows and 30 cm as a plant to plant distance on each bed.

The recommended dose of fertilizers at the rate of 100:50:50 kg acre^{-1} as $N:P_2O_5:K_2O$ was used and half the amount of the nitrogen (N) was applied during sowing while leftover was applied at hilling time (earthing-up). A complete dose of Phosphorus and Potassium accompanied with Zinc Sulphate @ 5kg acre^{-1} was applied at the time of sowing. The precautionary spray of Dithene M-45 at the required rate was also applied against early and late blight disease. Similarly, to prevent from sucking insects like whiteflies and aphids require doses of fungicides (Thiodan and Rivus Top) were also sprayed.

Data gathering, subsequent calculations, and analysis

Meteorological data: Daily meteorological data (i.e. temperature (ºC), pan evaporation (mm), rainfall (mm), etc.) were recorded at the metrological station of WMRC-UAF. Mean monthly climatic data of the experimental site is presented in Fig. 3. Evapotranspiration (ET_o) in mm was calculated by multiplying the evaporation rate with 0.70 (i.e. pan coefficient for class A pan). Maximum mean monthly (ET_o) was observed in October during both the years i.e. 2.43 mm and 2.80 mm respectively (Fig. 3) while throughout the growing season average ET_o was recorded 1.36 mm and 1.51 mm during the first and second year respectively.

Total rainfall was 82.30 mm and 29.70 mm during the growing season of the first and second year respectively. Effective rainfall (RF_e) was calculated using the following Eq. (6) (Dastane 1974; Nyvall & Tam 2005).

$RF_e = (RF-5)\times 0.75.$ [mm] (6)

Where RF represents the daily rainfall and RF_e is the effective rainfall in mm.

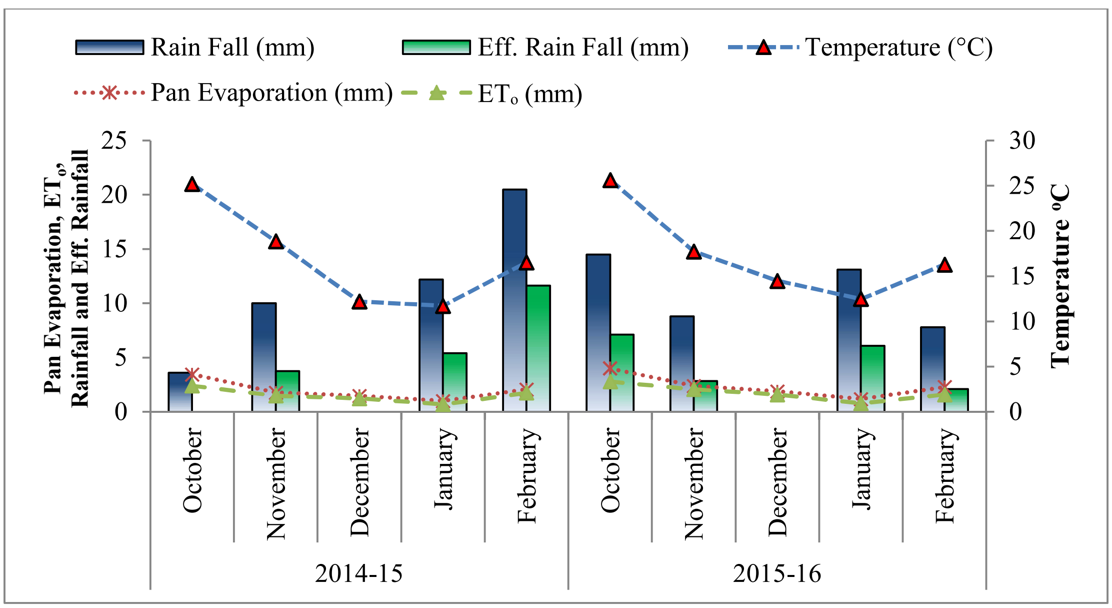

Fig. 3. Showing mean monthly pan evaporation rate (mm), ET_o (mm), rainfall (mm), effective rainfall (mm), and temperature (ºC) during the growing season for both years.

Six RF_e events were occurred in the first season having the highest value of 11.63 mm during February, while four events were perceived during the second growing season with 7.13 mm of highest RF_e (Fig. 3).

Physical parameters of potato tubers: To calculate the physical parameters of potato tubers, each tuber of an individual plant from harvested samples of each replication was subjected to physical measurements. Physical parameters (i.e. length, thickness, diameter, weight analysis, and actual volume) were measured and these measurements were set into further calculations (i.e. geometric mean diameter, surface area, shape index, sphericity, and calculated volume of the tubers). A digital Vernier Caliper with an accuracy of 0.01mm was used for measuring the three dimensions of tuber i.e. length, thickness, and diameter. Similarly, for weight analysis, digital balance with 0.01g accuracy was used.

The geometric mean diameter of tubers (D_{gm}) was calculated by using the following equation as described by Mohsenin (1986).

$D_{gm} = \sqrt[3]{L \times T \times D}.$ [cm] (7)

The surface area of the potato tubers was determined according to Baryeh (2001) using the following formula.

$S.A = \pi \times (D_{gm})^2.$ [cm^2] (8)

Shape Index (SI) was used to categorize the tubers into two classes. If SI is ≤ 1.5 and >1.5 tubers are classified as spherical and oval in shape respectively. SI of the selected tubers was calculated according to Ismail (1988).

$S.I = \frac{L}{\sqrt{D}}.$ [-] (9)

Where S.I is shape index and L, T, and D are length, thickness, and diameter of tuber in cm respectively.

Another approach was used to calculate the sphericity of the tubers. The sphericity of potato tuber was calculated using the following formula (Ahmadi *et al.* 2008).

$\Phi = \frac{D_g}{L} \times 100.$ [%] (10)

Where Φ is sphericity (%) of the tuber, D_{gm} is the geometric mean diameter (cm) and L is the length (cm). A similar approach was used by Dalvand (2011) for Φ calculation in Iran for potato tuber.

The actual volume (V_{act}) of potato tubers was measured by placing the tuber in a cylinder filled with water. Thereafter, the weight of displaced water in (g) was noted and divided with a specific density of water in (g mm^{-3}) according to Stroshine & Hamannd (1994).

$V_{act} = \frac{W}{S_\rho}.$ [cm^3] (11)

Where V_{act} is the actual volume of tuber in cm^3, W is the weight of displaced water in g and S_ρ is the specific density of water in g cm^{-3}.

Calculated volume (V_{cal}) in cm^3 of individual tuber was determined using the following equation as described by Mohsenin (1986).

$V_{cal} = \frac{\pi}{6} \times (L \times T \times D).$ [cm^3] (12)

Where L, T, and D are the length, thickness, and diameter of potato tuber in cm respectively.

Physico-chemical properties of potato tubers: Particle density, bulk density, porosity, specific gravity, tuber dry matter percentage, tuber starch content, and total soluble solids were included in the physico-chemical properties of potato tubers. Particle density (P_ρ) in g cm^{-3} of potato tuber was calculated by dividing the weight of potato tuber (g) to the actual volume of tuber (cm^3).

$P_\rho = \frac{W}{V_a}.$ [g cm^{-3}] (13)

Where W is the weight of potato tuber in g and V_{act} is the actual volume of tuber in cm^3.

Bulk density (B_ρ) in kg m^{-3} of potato tubers was evaluated by dividing the weight of bulk tubers by its estimated volume (Ghabel *et al.* 2010). In this case, a bulk of tubers was put in the box, and then the box was vibrated to the tubers incorporation. The porosity (φ) of a bulk sample of potatoes was calculated from values of particle density and bulk density using the following formula (Mohsenin 1986).

$\varphi = \frac{P_\rho - B_\rho}{P_\rho} \times 100.$ [%] (14)

Where B_ρ is the bulk density and P_ρ is the particle density of potato tubers.

Dry matter content directly influences the oil absorption rate in fried products and the yield of processed products. Therefore, the processor tries to get potato tubers with the best dry matter content to minimize oil absorption rates and maximize processed yield. The dry matter content of the tubers was determined gravimetrically by drying finely sliced tuber samples in an oven at 105 °C till constant weight for at least a day (i.e. 24 hours) (Öztürk *et al.* 2010).

The specific gravity of potato tuber is another important quality criterion of potato which directly linked with production and quality of the processed stuff. For this purpose, potato tuber samples (Five Kg) from each treatment were taken, first weighed in air (W_{air}) on an electric balance, and then the same sample was reweighed using a tared weighed basket by suspending them in water (W_{water}). Specific Gravity (S.G) was calculated as follows and a similar approach was used by Abbas *et al.* (2011).

$S.G = \frac{W_a}{W_a - W_w}.$ [-] (15)

Total Soluble Solids (TSS) or (^{0}Brix Test) are also significant in controlling microorganisms in food items. The higher TSS value showed that less water is available for microorganisms to grow. TSS was found using a hand refractometer by putting a couple of juice drops on the uncontaminated prism of the refractometer at room temperature and reading was taken from the scale. A similar procedure was repeated three times to obtain the average value for each treatment. Starch content was measured by following the protocol as described in the FAO Manual of food quality control (Martin 1979).

Yield of potato tubers and crop water productivity: The yield of potato tubers was calculated by harvesting three samples from randomly selected locations of every single replication while each sample size was 1 m^2 in area, and thereafter average value was converted into tons acre^{-1}. The average number of potato tubers per plant was also assessed by counting harvested tubers of each plant in three 1 m^2 areas. Afterward, potato tubers were graded into three categories based on their weights i.e. small tubers having weight < 50 g, medium tubers were 50-150 g in weight, and large tubers were >150 g in weight. Potato grading helps in the proper marketing of potato to get higher net returns.

Crop Water Productivity (CWP) was also determined using the following equation (Eq. 7) for all the treatments according to Wichelns (2014) and Siyal *et al.* (2016).

Crop water productivity $= \frac{T \quad y \quad (K/h)}{T \quad ir \quad w \quad u \quad (m^3/h)}$. [Kg m^{-3}] (16)

Statistical Analysis: The collected data were analyzed statistically to compute the final results using "Statistix 8.1" software. The two year's data were subjected to Analysis of Variance (ANOVA) (Gomez & Gomez 1984) and a comparison of means differences among different treatments was done using LSD test at a 5% level of significance.

RESULTS

Irrigation: Irrigation was applied to each treatment when soil moisture reached threshold moisture content as shown in Figs. 4 and 5 for both years respectively. Total net irrigation applied inclusive of effective rainfall in mm to all the treatments was ranging from 217 mm (MAD_{50}) to 256 mm (MAD_0) during the first year. While, in the second-year net irrigation applied was 260 mm (MAD_{35}) followed by 253 mm (MAD_0), 248 mm (MAD_{20}), and 240 mm (MAD_{50}). Treatment MAD_0 received irrigation almost on daily basis (to maintain 0% depletion) except the days when there were chances of effective rainfall. Moreover, it is quite laborious to schedule irrigation at MAD_0, because it involves vigorous soil moisture data monitoring and applying frequent irrigations to maintain soil moisture in the root zone at field capacity.

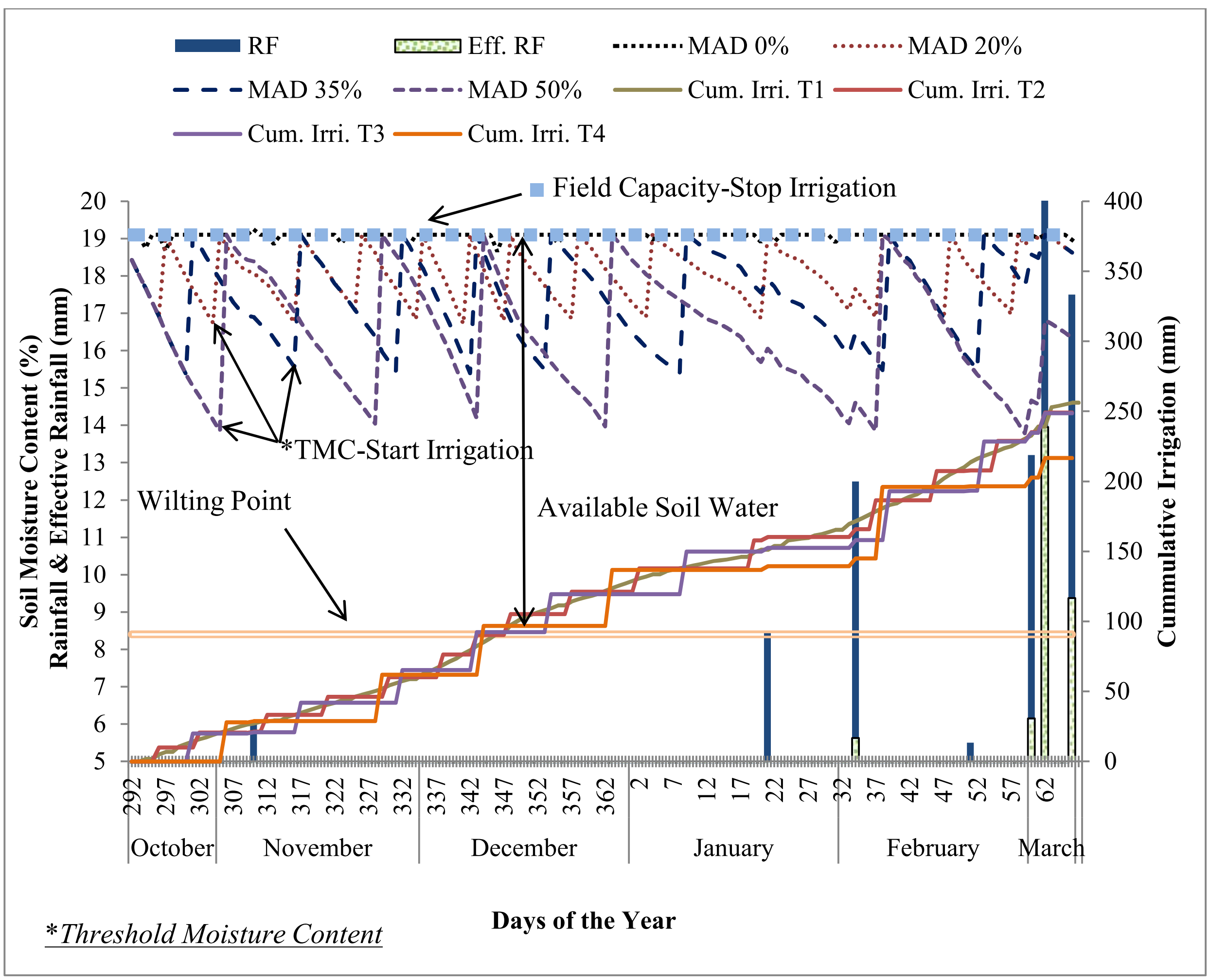

Fig. 4. Showing fluctuations in soil moisture content (%) within the available soil water profile as affected by different MAD levels (i.e., advanced irrigation$_{0\%}$ to delayed irrigation$_{50\%}$) throughout the growing season, rainfall & effective rainfall (mm) and cumulative irrigation applied to each treatment for the year 2014-15.

While, there were (14, 15) irrigation events in treatment MAD_{20} followed by MAD_{35} (8, 9) and MAD_{50} (5, 6) during both the years respectively (Figs. 4 and 5) revealing the fact that the frequency of irrigation depends on different MAD levels. Irrigation requirement at the end of mid growth stage was higher than other growth stages and it reveals that irrigation requirement by the crop depends on the growth stage too.

It can be seen from Figs. 4 and 5 that soil moisture curves within the available soil water profile showed a jump whenever there were events of effective rainfall.

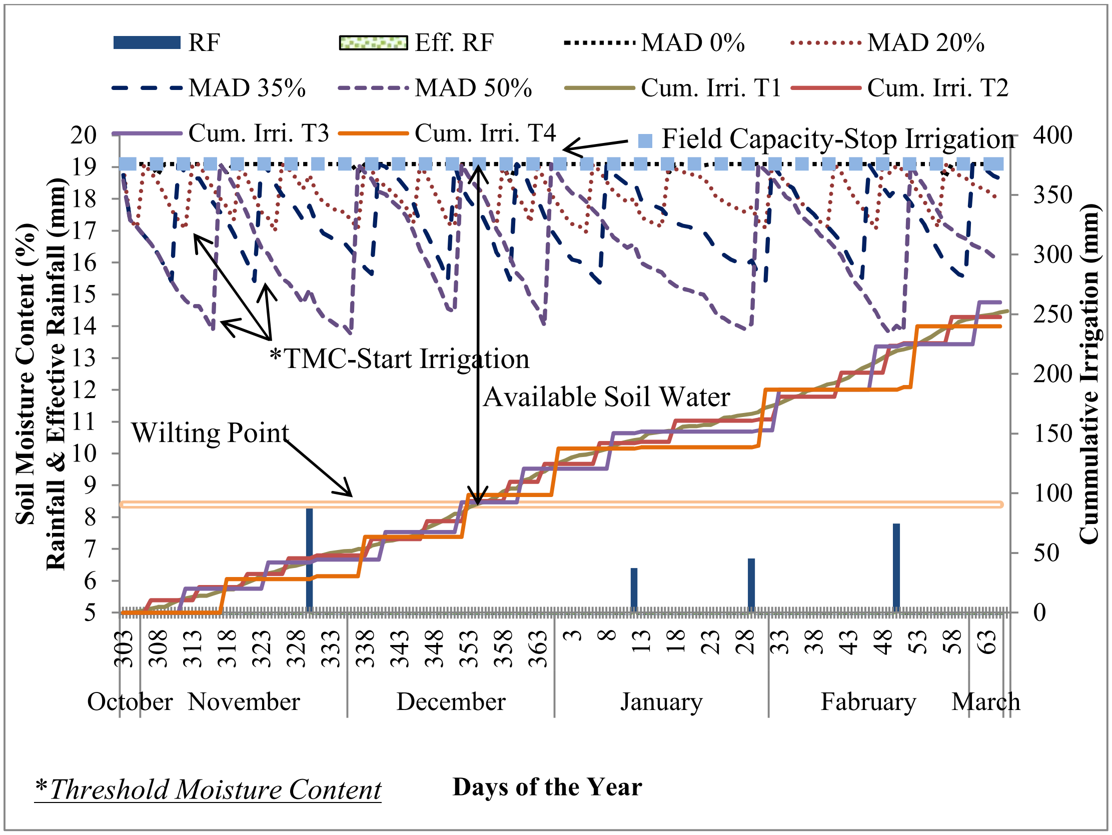

Fig. 5. Showing fluctuations in soil moisture content (%) within the available soil water profile as affected by different MAD levels (i.e., advanced irrigation$_{0\%}$ to delayed irrigation$_{50\%}$) throughout the growing season, rainfall & effective rainfall (mm) and cumulative irrigation applied to each treatment for the year 2015-16.

Physical parameters of potato tuber: After measuring the three-axis of randomly selected harvested potato tubers from all the treatments, results revealed that different treatments significantly ($p \leq 0.05$) affect the length of the potato tubers. The maximum length of tuber was observed in MAD_{35} (9.17, 8.98) for both the years respectively followed by MAD_{20}, MAD_0, and MAD_{50} further results are listed in Table 2. Similarly, tuber thickness, diameter, and subsequently geometric mean diameter (D_{gm}) were also significantly affected by the different MAD levels during both the years at $p \leq 0.05$. A similar trend was observed while calculating the surface area of potato tubers. The maximum surface area in cm^2 was noted at MAD_{35} (142.62, 145.21) during both years. The shape index of potato tuber was statistically non-significant but the maximum value was observed at MAD_{35} (1.59) during the first year. Further calculations showed that sphericity (**Φ**) percentage was not significantly ($p \leq 0.05$) affected by the different MAD level treatments (Table 2) which indicate that the shape of potato tubers doesn't resemble with the perfect sphere.

Hence, all the treatments yielded oval-shaped potato tubers. Different treatments significantly affect the actual volume of potato tubers at $p \leq 0.05$ revealing the fact that one or more treatments are different significantly. The maximum volume was noted at MAD_{35} (i.e., 175.67, 157.00 in cm^3) for both the years respectively (Table 2) while a similar trend was observed in the calculated volume of tubers.

Table 2. Physical measurements and associated calculations of potato tubers as influenced by different MAD level treatments under bed sowing for both the years.

Year	Treatments	Tuber Length	Tuber Thickness	Tuber Diameter	Geo. Mean Diameter	Surface Area	Shape Index	Sphericity	Actual Vol. of Tuber	Calculated Vol. of Tuber
		L	T	D	D_{gm}	SA	S. I	Φ	V_{act}	V_{cal}
			- - - - - - - cm - - - - - - -			cm^2	- - -	%	- - - - - cm^3 - - - - -	
2014-15	***MAD_0***	6.67b	4.33b	4.29ab	4.97bc	78.34bc	1.58a	76.18a	70.33bc	66.16bc
	MAD_{20}	7.42b	4.73b	4.83a	5.52b	95.75b	1.56a	74.50a	84.67b	88.32b
	MAD_{35}	9.17a	6.47a	5.17a	6.74a	142.62a	1.59a	73.53a	175.67a	160.54a
	MAD_{50}	5.57c	3.82b	3.5b	4.2c	56.04c	1.53a	77.90a	48.50c	40.10c
	CV	6.49	13.33	12.76	8.94	15.45	11.42	4.00	18.55	20.21
	LSD (0.05)	0.93	1.29	1.13	0.96	28.76	0.36	6.04	35.14	35.84
2015-16	***MAD_0***	6.47b	4.3bc	4.09b	4.82bc	73.42bc	1.58a	76.75ab	95.67ab	59.67bc
	MAD_{20}	7.17b	5b	4.52ab	5.44b	92.98b	1.52a	75.31ab	85.00b	84.53b
	MAD_{35}	8.98a	6.38a	5.5a	6.80a	145.21a	1.52a	74.62b	157.00a	164.79a
	MAD_{50}	5.57c	3.47c	3.83b	4.17c	54.92c	1.56a	78.89a	41.67b	38.59c
	CV	5.54	9.25	11.89	6.57	11.15	8.89	2.47	34.43	14.50
	LSD (0.05)	0.78	0.88	1.07	0.70	20.42	0.27	3.78	65.24	25.18

Note: *Means followed by the same letter within a column are not significantly different at 5% level of significance,* **LSD:** *Least Significant Difference, and* **CV:** *Coefficient of Variation.*

Physico-chemical properties of potato tubers: Treatment *MAD_{35}* showed higher values of particle density (i.e. 1.09, 1.10 in g cm^{-3}) for both the years though there were no significant differences among the means of all treatments ($p \le 0.05$). Whereas, different MAD level treatments significantly affect the bulk density (kg m^{-3}) of potato tubers. The maximum value of bulk density was noted at *MAD_{20}* i.e., 594.50 and 585.00 during the first and second year respectively (Table 3). In the packaging of potato tubers, bulk density is an important factor to be considered. The porosity of tubers was not affected significantly by the different treatments at $p \le 0.05$, while maximum porosity was observed at *MAD_0* (48.88%, 48.79%) and *MAD_{50}* (48.54%, 48.28%) during both years respectively (Table 3).

Table 3. Physico-chemical properties of potato tubers influenced by different MAD level irrigation regimens during the 2014-15 and 2015-16.

Year	Treatments	Particle density	Bulk density	Porosity	Specific gravity	Tuber dry matter	Tuber starch content	Total soluble solids
		g cm^{-3}	kg m^{-3}	%	- - -	- - - % - - -		^{0}Brix
2014-15	***MAD_0***	1.09a	554.17bc	48.88a	1.075a	20.08ab	11.68a	5.73a
	MAD_{20}	1.06a	594.50a	43.47a	1.073a	19.59b	11.41a	5.38a
	MAD_{35}	1.06a	563.67b	46.65a	1.079a	20.86ab	11.51a	5.79a
	MAD_{50}	1.08a	547.67c	48.54a	1.080a	21.64a	11.93a	6.03a
	CV	10.49	0.89	12.34	0.64	4.93	3.30	7.22
	LSD (0.05)	0.22	10.04	11.56	0.014	2.02	0.77	0.83
2015-16	***MAD_0***	1.09a	558.17c	48.79a	1.072a	18.30b	11.59a	6.01a
	MAD_{20}	1.08a	585.00a	45.57a	1.067a	20.66ab	11.35a	5.56a
	MAD_{35}	1.07a	567.67b	47.09a	1.069a	20.93ab	12.06a	5.76a
	MAD_{50}	1.07a	553.00d	48.28a	1.085a	22.57a	11.90a	6.25a
	CV	4.99	0.28	5.51	1.19	8.57	3.92	9.95
	LSD (0.05)	0.11	3.14	5.22	0.026	3.53	0.92	1.17

Note: *Means followed by the same letter within a column are not significantly different at 5% level of significance,* **LSD:** *Least Significant Difference, and* **CV:** *Coefficient of Variation.*

It is evident from Table 3 that *MAD_{50}* (1.08, 1.09) is at par with other MAD level treatments in terms of specific gravity of potato tubers for both years but differences among the means are statistically non-significant ($p \le 0.05$). A significant trend was observed in tuber dry matter percentage and the maximum value was observed at MAD_{50} (21.64%, 22.57%) which means different MAD levels affect the percentage of dry matter. The outcomes of the current study (Table 3) exposed that tuber starch content was statistically non-significant ($p \leq 0.05$) and ranging from 11.41% to 12.06%, which shows that starch content is a varietal parameter and not affected by different MAD levels. Different MAD level treatments didn't affect the TSS (^{0}Brix) significantly while treatment MAD_{50} (6.03, 6.25) was at par with other treatments during both years. In nutshell, it was observed that several physical and chemical properties of potato tubers are genetic or varietal based. But physical dimensions of a potato tuber are significantly affected by different MAD levels.

Crop yield and water productivity: Average number of potato tubers were statistically analyzed and found non-significantly affected by the different MAD levels under bed sowing.

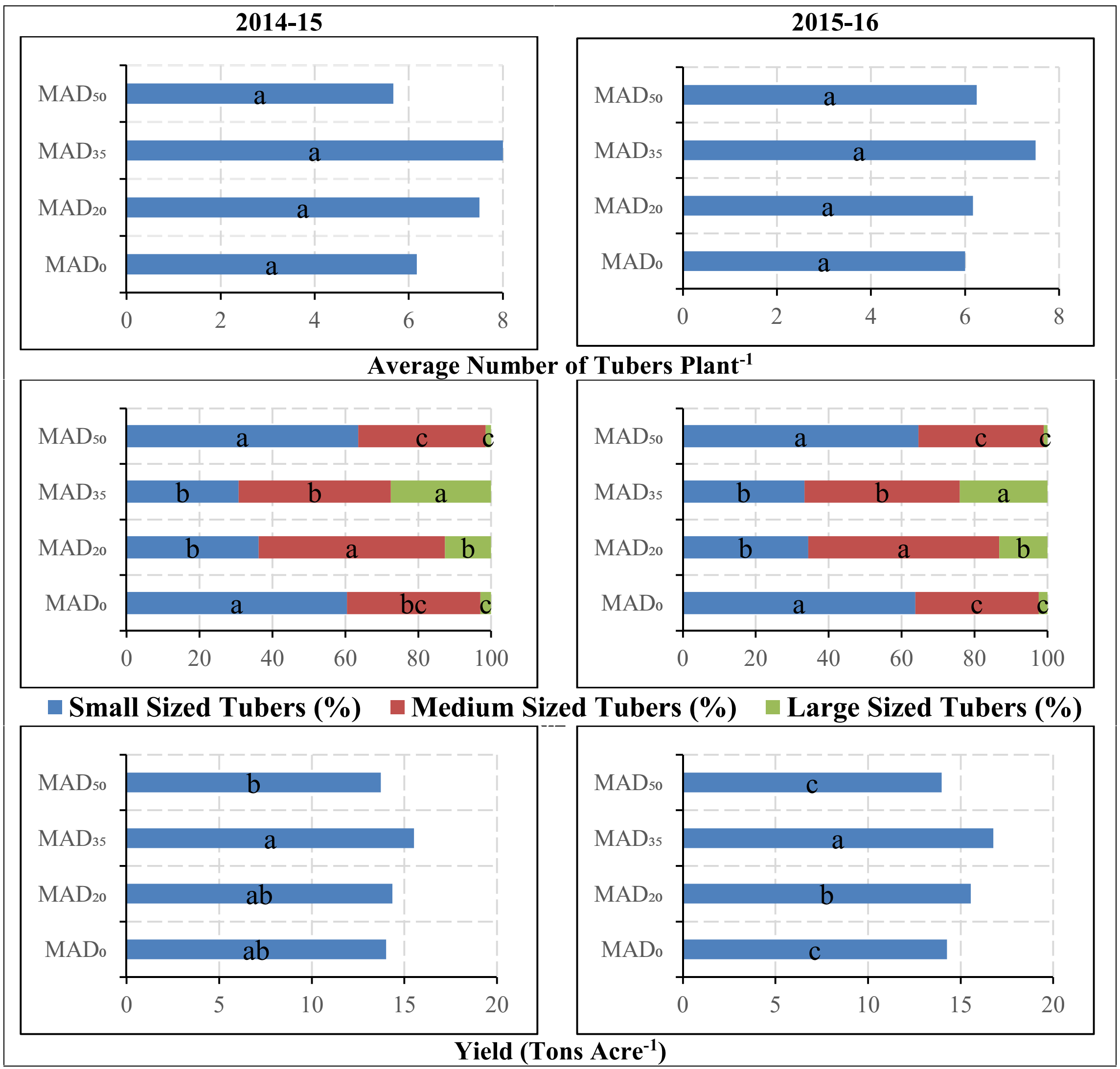

Fig. 6. Showing the average number of tubers plant^{-1}, percentage of different categorized tubers (i.e. small, medium, and large tubers), and potato yield in tons acre^{-1} during both years. [*Note: The bars labeled with the same letters exhibit that means are statistically non-significant at p ≤ 0.05*]

However, on average 6-8 tubers plant^{-1} were recorded among all the treatments. The percentage of the small, medium, and large-sized tubers was significantly ($p \leq 0.05$) affected by the different treatments. For both years, treatments MAD_0 and MAD_{50} were at par with the others in terms of small tubers. Treatment MAD_{20} was found significantly ($p \leq 0.05$) superior to the other treatments in terms of medium-sized tubers production for both years (Fig. 6).

While, the percentage of large size tubers was significantly affected by the different MAD level treatments and results revealed maximum large size tubers in MAD_{35} (27.53%, 24.00%), further data is shown in Fig. 6. The statistical analysis of potato yield in tons/acre for the different treatments showed significant results at $p \leq 0.05$ (Fig. 6). The highest yield in tons acre^{-1} was observed in MAD_{35} treatment i.e. 15.52 tons acre^{-1} and 16.76 tons acre^{-1} for the first and second year of the experiment respectively followed by MAD_{20} (i.e. 14.35, 15.55 in tons acre^{-1}). CWP was significantly influenced by different MAD levels treatments at $p \leq 0.05$ (Fig. 7), maximum productivity of water was seen in treatment MAD_{35} i.e. 14.19 and 14.64 in kg m^{-3} during both the years.

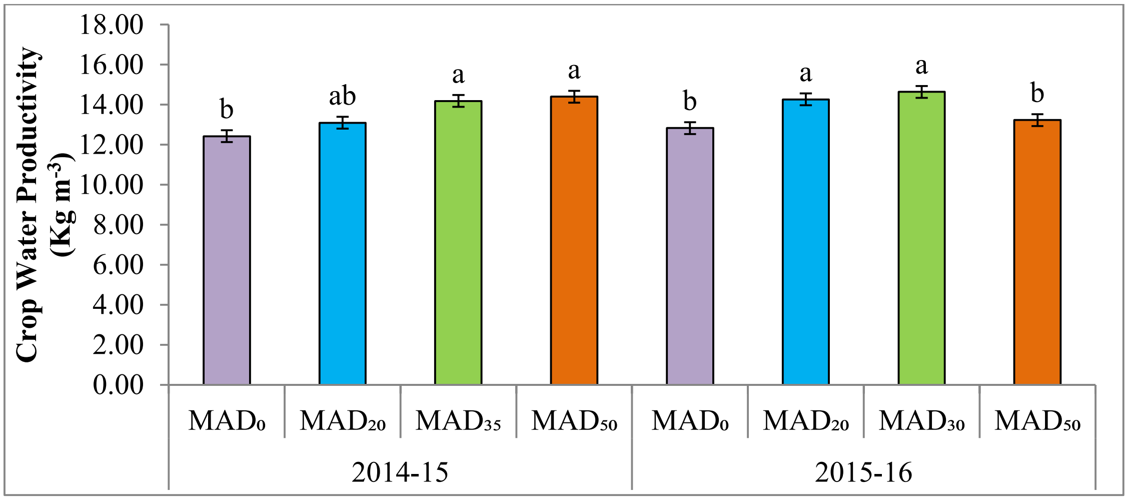

Fig. 7. Showing CWP in kg m^{-3} influenced by different allowed depletion levels during both the years. [*Note: The same letters outside the bars of the CWP exhibit that means are statistically non-significant at $p \leq 0.05$*]

DISCUSSION

Crop production can be enhanced by adopting efficient sowing and irrigation practices (Waqas *et al.* 2021). A drip irrigation system provides the number of opportunities in terms of higher yield with more savings in irrigation water. MAD level approach through drip irrigation system describes how much and when to irrigate. The current study work revealed different results related to yield, physical dimensions, and physico-chemical properties of potato tubers. The reduced length of tubers was observed in treatment MAD_{50}, which might be due to the delayed availability of moisture at bulking stage. While in treatment MAD_{0} and MAD_{20} length of tubers shortened might be due to the aeration problem because of excess availability of moisture or advanced application of water from the required/optimum schedule.

Different MAD levels affect the geometric mean diameter of potato tubers. Hence, the MAD level factor may be added to the factors discovered by Gebreselassie (2013), who describes that D_{gm} of potato was significantly influenced by variety and growing environment. The shape index was greater than 1.5 among all the treatments (Table 2) which endorse that the shape of potato tubers was oval. Moreover, results revealed that different MAD levels didn't affect the shape of potato tubers and this might be affected by the genetic makeup of the potato variety. Therefore, tuber shape is a morphological characteristic and this result coincides with Storey & Davies (1992), they described that the shape of tubers is largely the varietal characteristics. Similarly, Custers (2015) also studied genes that are influencing potato tuber shape. Earlier, Abbas *et al.* (2012) describe that the shape of potato tubers is controlled by genetic factors and to some extent, the environment may also play role in it.

Tabatabaeefar (2002) noted the average sphericity of four Iranian potato varieties i.e. 78.75%. Maximum sphericity and percentage of small-sized tubers were observed in treatment MAD_{50}. Moreover, results depicted that the more the small sized tubers, the more their shape will be spherical as compared to tubers that fall in the category of medium or large sized-tubers. These results confirm the findings of Tsegaye (2019). Dalvand (2011) also worked on the porosity of tubers and found a mean value i.e. 35.64%.

Food processing industries are very much conscious about the two main factors i.e. specific gravity and dry matter of potato tubers. Maximum specific gravity was observed in treatment MAD_{50} although the results are non-significant. Findings of specific gravity from this study work may be combined with the results of Pervez *et al.* (2013), they observed non-significant results of specific gravity of "Desiree" cultivar at different levels of SOP (i.e. sulfate of potash). During both the years, maximum tuber dry matter percentage was observed at MAD_{50} (Table 3) and the findings are contrary with Toolangi (1995), who describes that tuber dry matter content is strongly a genetic-based attribute and consistent with Amer *et al.* (2017), they reported higher values of dry matter and specific gravity of potato tubers at 45% of ASW. This scenario reflects that fertilizer level and time of irrigation both are important factors in determining the tuber dry matter content.

Specific gravity and dry matter percentage of potato tubers are the two basic indicators of the processing quality and reflect the amount of starch present (Abbas *et al.* 2011). Both advanced and delayed irrigation practices didn't have any significant effect on starch content and TSS of potato tubers. Nevertheless, there are number of other important factors (i.e. variety and environment) that have significant effects on the starch percentage of potato tuber (Kumar *et al.* 2004). Pervez *et al.* (2013) reported that TSS was significantly affected by the different levels of SOP.

Physico-chemical properties of potato tubers were not affected by the different MAD level treatments excluding bulk density and tuber dry matter. This indicates that there might be any other factors that affect these parameters. Abbas *et al.* (2011) describe that genotype and variety of potato plays an important role in chemical properties.

The maximum number of potato tubers plant^{-1} was observed at MAD_{35} although the results are non-significant and this might be due to the optimum irrigation schedule. Past studies reported a reduction in the total number of tubers plant^{-1} when moisture depletion occurred during tuber initiation (Gianquinto *et al.* 1997). Treatment MAD_{50} yielded a maximum percentage of small-sized potato tubers and their bulking might be squeezed due to the delayed availability of moisture in the root zone. Similarly, in MAD_0 (i.e. advanced irrigation) there might be aeration problem in the root zone due to continuous application of water resulting in overdue maturity of tubers. The maximum percentage of large size tubers was observed at MAD_{35} and this is near to Amer *et al.* (2017), they have observed the maximum percentage of large tubers at 25% MAD level.

Maximum yield of potato tubers was observed in treatment MAD_{35} and this might be due to the availability of optimum, required, and timely application of irrigation. Results of treatment MAD_0 and MAD_{50} indicate that both advance and delayed irrigation practices have adverse effects on yield (Fig. 6) and the moderate MAD level (i.e. 35% of ASW) is the most favorable one. Kashyap & Panda (2003) also studied the effects of different MAD levels on potato crop and described that, increase in MAD from 45% to 75% results significant reduction in tuber yield and other crop parameters. Afzaal *et al.* (2020) also studied the impact of pressurized irrigation systems on potato crop and observed the highest potato yield (i.e. 38,327 kg ha^{-1}) in the sprinkler irrigation practice. Sarker *et al.* (2019) studied the Alternate Furrow Irrigation (AFI), Fixed Furrow Irrigation (FFI), and Every Furrow Irrigation (EFI) methods for potato crop and found non-significant dry matter tuber yield at $p<0.05$ with AFI and EFI while significant at $p<0.01$ as compared to FFI. Salih *et al.* (2018) also studied different irrigation intervals on tuber yield. They found a significant reduction in potato tuber yield and an increase in WUE by increasing irrigation intervals (days). Hence, the number of irrigation events significantly affects the yield of the potato crop. Therefore, results revealed that both advanced and delayed irrigation can affect the yield of the potato crop. So, the optimum number of irrigations (Figs. 4 and 5) in treatment MAD_{35} (i.e. 35% of ASW) might be an additional factor of higher yield during both the years.

The higher yield in treatment MAD_{35} might be due to the most favorable availability of moisture and proper setting of MAD level. These results coincide with the findings of Eiasu *et al.* (2007), they observed a significant impact of moisture stress at the highest MAD levels and describes that a 40% MAD level doesn't significantly influence the tuber yield and concluded that yield significantly decreases with an increase in MAD Level. Similarly, Ijaz-ul-Hassan *et al.* (2021) also studied the 15%, 30%, 45%, and 60% MAD levels to maximize the water use and to enhance the crop yield, and noticed the maximum water saving with 30% MAD level followed by 60%, 15%, and 45% MAD levels. Furthermore, another research study reported that irrigation at 100% of maximum evapotranspiration and the highest fertilizer rate gave the maximum yield (Ierna & Mauromicale 2018). Hence, it is suggested that depletion in ASW should not be more than 35% for optimal potato production. The number of potato tubers plant^{-1} and the size of tubers might be another factor of yield increase at MAD_{35}. This finding coincides with Mehdi *et al.* (2008), they describe that yield increase depends on the higher number of tubers plant^{-1} and tuber size. Whereas, Shaheen *et al.* (2019) reported that foliar spraying of amino acids mixture @ 2.5 cm^3 L^{-1} or chitosan @ 5.0 cm^3 L^{-1} is the most effective treatment in enriching vegetative development, potato tubers yield, and other quality factors. Moreover, Daccache *et al.* (2011) estimated the climate change impact using the SUBSTOR-Potato model for the 2050s, and observe (3-6%) slight addition in the potato yield, and predicted the future irrigation requirements to elevate by 14-30%.

Sustainability in agriculture and food security could be attained by increasing water productivity. In other words, enhancing agricultural yield per unit of irrigation water, and this can only be achieved through improved on-farm water management techniques. Higher CWP in treatment MAD_{35} (Fig. 7) is due to the fact that this treatment yielded more large size tubers and gain more production. Similarly, many researchers reported improvement in CWP under drip irrigation systems through different irrigation regimens (Ati *et al.* 2012; Eid *et al.* 2020).

In brief, both surplus water and water stress at an early stage (i.e. tuber initiation stage) can adversely affect the number of tubers plant^{-1}, yield, and other growth parameters. To achieve optimum tuber size, delay in irrigation should be avoided during midseason (i.e. tuber bulking stage). Therefore, irrigating at 35% MAD level is recommended as one of the best irrigation practices for effective potato production under drip irrigation system, leading towards precision farming.

Conclusions: Precise use of water resources is the dire need of the day due to increasing water scarcity issues in Pakistan and worldwide. To overcome this issue, every drop of water must be used wisely, considering when, how much, and where to apply. Physical parameters and physico-chemical properties are the most important quality factors of potato tubers, which are highly considered in the potato industry. The present study assesses the benefits of using different irrigation schedules through drip irrigation for sustainable on-farm water management. The statistical results revealed that different MAD level irrigation regimens significantly affect the tuber length, thickness, diameter, geometric mean diameter, surface area, actual and calculated volume of potato tuber. Although, the shape index and sphericity of potato tubers are not significantly affected by the different treatments and strongly depend on the variety and genetic makeup.

Different MAD levels significantly affect the bulk density of potato tubers and the maximum value was observed at MAD_{20} (i.e. 20% MAD level) while results of particle density were non-significant for both the years of the experiment. These parameters are very imperative while packing, storing, and exporting the potatoes worldwide. Some of the physico-chemical characteristics didn’t significantly affected by different treatments i.e. porosity, specific gravity, and tuber starch content. The different MAD levels significantly ($p\leq0.05$) affect the different categories of potato tubers (i.e. small, medium, and large). The 35% of ASW (MAD_{35}) showed the maximum percentage of large-sized tubers followed by MAD_{20}. The maximum yield of potato tubers in tons acre^{-1} and CWP during both the years were also observed at 35% MAD level.

It was concluded that advance and delayed irrigation practices adversely affect the physical parameters and yield of potato tubers. While different MAD levels didn’t have any notable effects on some of the chemical properties that truly depend on internal vigor or genetic traits of seed. Therefore, the findings of this study recommended that efficient and timely application of irrigation water (i.e. irrigation at 35% of ASW) can produce more yield with large-sized tubers. However, advanced and delayed irrigation practices from the optimum schedule aren’t recommended for potato crop under raised bed sowing. The findings of this study have potential implications, as it provides some important guidelines for the farmers and processing industries. Moreover, future research studies on fertigation management in potato crop under raised bed sowing method is suggested to enhance yield and further improvements in other growth parameters.

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