

# Impact of water requirement on yield productivity of potato crop using lysimeters under arid climate

## Abstract

Here, we address the issue of water management for potato (*Solanum tuberosum* L.) crops under arid conditions in Saudi Arabia over a 5-year period (2011–2016). Daily evapotranspiration for irrigated potato crops (ET<sub>c</sub>) was determined over a period of three successive seasons. Non-weighing (drainage) lysimeters were used in four regions: Riyadh, Qassiem, Eastern Province, and Al-Jouf. Crop coefficients (K<sub>c</sub>) were determined using lysimetric data and an alfalfa-based reference crop evapotranspiration (ET<sub>r</sub>) during each growing season. Measured (M-ET<sub>r</sub>) and predicted, (P-ET<sub>r</sub>) for different regions were compared. Comparisons between M-ET<sub>r</sub> and P-ET<sub>r</sub> show higher trends for the measured values in all regions, with averages of 5.72 mm/d, 4.42 mm/d, 5.06 mm/d, and 7.94 mm/d for the Riyadh, Qassiem, Eastern Province, and Al-Jouf regions, respectively. Differences in the ET<sub>r</sub> and ET<sub>c</sub> were also observed among the regions due to geographic and climatic variations. In addition, the water-use efficiency of potato crops was generally highest (5.45 kg m<sup>-3</sup>) in Riyadh and lowest (1.54 kg m<sup>-3</sup>) in Qassiem. Analysis of projected net returns for irrigated potato production revealed that greater economic potential exists.

**Keywords:** crop coefficient, lysimeter, penman-montieth, reference evapotranspiration, water economic return

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FS Mohammad,<sup>1</sup> HM Al-Ghobari,<sup>1</sup> MSA El Marazky<sup>1,2</sup>

<sup>1</sup>Department of Agricultural Engineering, College of Food and Agriculture Sciences King Saud University, Riyadh 11451, Kingdom of Saudi Arabia

<sup>2</sup>Agricultural Engineering Research Institute (AEnRI), Agricultural Research Centre, Egypt

**Correspondence:** MSA El Marazky, Agricultural Engineering Research Institute (AEnRI), Agricultural Research Centre, P.O. Box 256, Giza, Egypt, Email elmarazky58@gmail.com, melmarazky@ksu.edu.sa

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## Introduction

The Kingdom of Saudi Arabia (KSA) is currently 121% self-sufficient in potatoes.<sup>1</sup> In 2010, the country's potato crop encompassed a land area of 6,941 ha, with production of approximately 176,077 tons.<sup>2</sup> The successful irrigation of potato requires an understanding of both irrigation and scheduling methods, as a regular water supply is needed to secure high yields.<sup>3</sup> Potato is often considered to be a high-water-use crop,<sup>4</sup> with yield quantity greatly influenced by the amount of applied water.<sup>5,6</sup> In agriculture, quantifying evapotranspiration (ET) is essential for effective irrigation management.<sup>7</sup> In the KSA, water requirements for potato crops average around 590 mm and 710 mm in the autumn and spring seasons, respectively.<sup>8</sup> In eastern Saudi Arabia, Al-Omran and Shelby<sup>9</sup> estimated the total crop water requirement of potatoes to be approximately 520 mm, whereas Al-Ghobari<sup>10</sup> calculated a water requirement of 416 mm for the winter season in Najran. In contrast, Wright and Stark reported seasonal water consumption values in irrigated areas of Oregon and Washington between 640 mm and 700 mm, demonstrating the variation that exists in water use depending on factors such as environment, season, and rate of crop growth. Lysimeter is generally considered as the criterion system for estimating crop evapotranspiration (ET<sub>c</sub>) and crop coefficients (K<sub>c</sub>); as such, measurements of the water requirements of potato crops can be attained using lysimeters, which provide more reliable measurements of ET<sub>c</sub> that, in turn, allows for more precise estimates of irrigation water depths.<sup>11,12</sup> ET<sub>c</sub> measurements are used for different crops grown in Saudi Arabia,<sup>13,14</sup> and a standardized reference ET approach is commonly used to determine daily reference ET.<sup>15</sup> The crop coefficient varies through the course of the growing season, depending on the growth stage of the crop.<sup>16</sup>

Moreover, it has been shown that K<sub>c</sub> can vary within a crop due to differences in climate,<sup>17</sup> cultivation practice,<sup>18</sup> and surface situations.<sup>19</sup> Published K<sub>c</sub> values<sup>20,21</sup> typically derive from lysimeter-based environmental studies in which crops are grown under special climatic, irrigation, soil, and surface situations. The K<sub>c</sub> and

associated measurements of ET can be used to develop, calibrate, and test important ET-process models; as such, K<sub>c</sub> values obtained from previous studies have been calibrated via experimental research with different pedoclimatic conditions by many researchers.<sup>22–24</sup> Alkaeed et al.,<sup>25</sup> emphasized the need for local calibration by adjusting K<sub>c</sub> to match specific localized field conditions. Ferreira<sup>26</sup> have shown that the seasonal values of K<sub>c</sub> for potatoes are 0.87–0.85, whereas Kashyap<sup>27</sup> estimated K<sub>c</sub> values at different stages of potato crop development using measured ET<sub>c</sub>. Crop coefficients (K<sub>c</sub>) for potato have been documented significantly by previous studies to irrigate crops.<sup>28–30</sup> Carvalho et al.,<sup>12</sup> calculated K<sub>c</sub> values of 0.35, 0.45, 1.29, and 0.63 for potato (*Solanum tuberosum* L.) at different stages of crop development. Fan et al.,<sup>31</sup> calculated the water-use efficiency (WUE), ET, and yield (Y) for crops through statistical analyses of the data, whereas Salvador et al.,<sup>32</sup> applied WUE and water productivity indicators to evaluate irrigation performance, as well as the variance among irrigation methods and yields in the Ebro basin of Spain. Likewise, Andrés et al.,<sup>33</sup> used water productivity measure of the rule on both water quality and irrigation practices of the study area. In contrast, several researchers, including,<sup>34,35</sup> and Tarjuelo et al.,<sup>36</sup> have used economic models to optimize land use and water allocation to crops at the farm level and Pereira et al.,<sup>37</sup> developed deficit irrigation strategy, according to the estimates of economic indicators for the productivity and water use efficiency, taking into account the full awareness of the crop water requirements. The objectives of this paper were to 1) estimate the water requirements for potato crops and the WUE in four regions of Saudi Arabia, and 2) assess the potential economic returns of potato production and potato water use.

## Materials and methods

The approach we adopted to conduct this study fell into five categories: 1) site locations, 2) lysimeter construction and operation, 3) crop cultivation and management, 4) prediction and measurement of alfalfa (as reference-crop ET, or ET<sub>r</sub>) and potato ET<sub>c</sub>, and 5) statistical and economic analyses.

## Site location

Experiments designed to quantify the water requirement of potato crops were conducted in the four regions of the KSA where potato cultivation is most intense, namely Riyadh, Qassiem, Eastern

Province, and Al-Jouf. The experimental sites were situated in the fields of agricultural research centers of the Ministry of Agriculture and in the fields of agricultural companies within each region (Table 1). Meteorological data for each region are presented in Table 2.

**Table 1** Locations of the four regions included in this study

Experiments Location	Longitude	Latitude	Altitude (m)	Region
National Center for Research on Agriculture and Livestock in Riyadh	47	24	600	Riyadh
Agriculture Research Station, Qassiem Univ.	43° 59' E	26° 20' N	648	Qassiem
Agriculture Research Station King Faisal Univ. Hofuf.	49° 34' E	25° 22' N	179	Eastern
Alwatania Agricultural Company.	37	31	724	Aljouf

Source: Statistical Year Book, Ministry of Planning, 1998.

**Table 2** Average monthly climate data for the four regions

Region	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Riyadh	Temperature (°C)	16.9	19.7	23.8	28.8	32.7	34.4	35.5	35.2	32	26.8	21.9	18.1
	R. Humidity (%)	45.3	36.9	34.4	27.5	19.3	13.2	13.8	16.2	16.5	23.9	35.4	45.2
	Wind Speed (m/s)	3.9	4.1	4.4	4.1	3.3	2.8	3.3	2.9	2.7	2.7	3.5	3.7
	Sunshine (hr/d)	8.2	7.6	6.3	6.2	7.4	7.4	7.7	8.5	8.5	8.1	9.1	8.8
	Solar Radiation (MJ/m <sup>2</sup> .day)	16.6	16.6	20.9	23.3	25	26.1	25.7	25.2	23.5	21.2	17.5	14.8
	Rainfall (mm)	3	0	3	1	7	0	0	0	0	0	0	0
Qassiem	Temperature (°C)	12.7	14.8	18.8	24.8	30.4	33.3	34.4	34.7	31.9	26.9	19.9	14.8
	R. Humidity (%)	54.9	45.7	41.4	35.5	21	12.2	12.1	12.6	13.9	21.9	40.7	54.5
	Wind Speed (m/s)	2.6	3.1	3.3	3.4	3.4	3	2.9	2.6	2.4	2.4	2.7	2.6
	Sunshine (hr/d)	7.44	6.7	6.2	5.7	6.5	6.8	7.3	7.3	10.3	10	9.8	8.9
	Solar Radiation (MJ/m <sup>2</sup> .day)	12.6	13.9	18.7	21.5	24.6	26.2	26.4	25.4	22	19.6	14	10.8
	Rainfall (mm)	9.7	11.1	31	13.3	11.3	0	0	0	0.8	5.3	4.4	5.6
Eastern	Temperature (°C)	14.8	17	21.1	27.1	32.9	35.7	37.4	36.9	33.6	28.8	22.2	16.9
	R. Humidity (%)	57.2	51.9	47.3	40	28.3	23.9	25.1	31.9	36.7	43.4	50.9	59.3
	Wind Speed (m/s)	3.7	4.1	4.1	3.7	3.9	4.5	4.4	3.7	3.1	2.7	3.3	3.6
	Sunshine (hr/d)	8.16	7.6	6.2	6.2	7.27	7.4	7.8	8.6	8.6	8	9.3	9.2
	Solar Radiation (MJ/m <sup>2</sup> .day)	14.3	14.7	19.4	22.6	25.4	25.5	25.1	25.1	22.5	19.3	14.8	11.5
	Rainfall (mm)	12.2	1.3	13.5	15.6	12.9	0	0	2.9	0.6	8.6	0	0
Aljouf	Temperature (°C)	9.7	11.5	15.6	21.7	26.7	30.1	31.9	32.5	29.5	24.2	16.7	11.3
	R. Humidity (%)	59	48.1	39.2	29.6	21	17.2	18.3	18.5	20	31	46.2	56.3
	Wind Speed (m/s)	3.5	4.1	4.4	4.5	4.4	4.2	4.4	3.8	3.5	3.5	3.4	3.3
	Sunshine (hr/d)	5.1	4.8	4.6	4.8	5.2	5.6	5.9	6	6.2	6.1	6	5.6
	Solar Radiation (MJ/m <sup>2</sup> .day)	10.1	13.4	14.7	17.3	20	22.8	22.9	21.6	19.7	14.7	10.9	9.3
	Rainfall (mm)	8.1	3.9	4.1	1.16	0.3	0	0	0	2.9	11.18	1.3	11.4

Source: Statistical Year Book, Ministry of Planning, 1998

## Lysimeters construction and operation

Four drainage-type lysimeters (non-weighing) consisting of compacted to nearly normal soil field conditions were constructed, each extending over a surface area of 10m×6 m and to a depth of 1.5 m. These were located in the middle of alfalfa fields in order to minimize the effect of advection at the field edges, and one lysimeter was allocated for each region. Each lysimeter consisted of nine plots (2m×2m×1.5m) and weighed approximately 15 Mg, with

each plot containing a system of perforated pipes beneath the soil to facilitate drainage and polyethylene pipes laid out atop the soil to serve as surface irrigation systems. The irrigation systems included all necessary components, such as valves, water meters, and control boards, to ensure proper functioning. The lysimeter design and plot arrangement are shown in Figure 1. Tipping buckets were attached to the lysimeters for the purpose of collecting drainage water. The depths of the irrigation water added to the lysimeter, drainage water, and rainfall were monitored during the growing season. To improve

soil properties, organic matter in the form of peat moss was added at a rate of 50 kg/plot in the upper soil layer to a depth of 15 cm. Initially, all plots were flooded with water to facilitate leaching of the soil profile and decomposition of organic matter.



Figure 1 Layout of lysimeter plots.

## Crop cultivation and management

### Potato crops

Winter potato crops of the Spunta variety (*Solanum tuberosum* L.) were randomly sown in three plots within each lysimeter in the four regions for three successive seasons (2011–2016), whereas the other three plots were planted with alfalfa throughout the study period to measure  $ET_r$ . The planting and harvesting dates of the potato crops in the four regions are shown in Table 3. The entire experimental period was of 5 years (2010–2015); tasks such as lysimeter construction and installation, and the preparation of the plots were carried out over the first 2 years, and soil samples were collected from the lysimeter plots prior to the commencement of the experiment for the purposes of mechanical and chemical soil analyses. Three soil samples were extracted at three different depths (20 cm, 30 cm, and 60 cm) to determine the soil physical properties, with soils in all plots characterized as sandy loam. Potato tubers were planted manually in three rows at intervals of 30 cm and a depth of 0.10 m, with ridge heights of 20 cm and ridges separated by 75 cm.

Table 3 Planting and harvesting dates for the seasons 2011 – 2016

Region	Potato Crop		Avg. Yield (Mg/ha)
	Planting Date	Harvesting Date	
Riyadh	21-Oct	3-Feb	24.40 × 106
Qassiem	1-Sep	15-Dec	18.25 × 106
Eastern	15-Dec	30-Mar	17.69 × 106
Aljouf	15-Mar	13-Jun	26.97 × 106

### Fertilizers and pesticides

Fertilizers were added for the three cropping seasons in the same quantities and in accordance with the recommendations and schedules set out by the KSA Ministry of Agriculture. Nutrients N, P, and K were supplied at the rates of 200 kg/ha, 200 kg/ha, and 150 kg/ha, respectively. The P- and K-based fertilizers were utilized as basic doses prior to planting. Nitrogen was parted and distributed along with the irrigation water in all treatments for a period of early vegetative growth, and 100 kg/ha of potassium nitrate was applied to each plot following the tuber initiation stage. Pesticides were used to control

insects and pathogens and applied at times and rates commensurate with the prevailing norms for the region. The fungicide Penncozeb 75 DG was applied at a rate of 2.5 g/L for all treatments in the four locations during the three seasons, and plants were sprayed with the pesticide Imidor 200SL at a rate of 5 ml/10 L for insect control.

### Harvesting

Harvesting is a critical step in the potato production process and for future product marketing; the lysimeter plots in the four regions were harvested on different dates taking into account the specific conditions of each region over the three successive seasons. Potato production costs and sale prices were obtained from the Chamber of Farmer Association, and gross revenues were calculated by multiplying the first- and second-class yields and their prices. Finally, irrigation costs were calculated from data reported by Sener et al.<sup>38</sup>

### Water-use efficiency

Water-use efficiency (WUE) is defined as the yield obtained per unit of water consumed, whether from irrigation or the total amount of water received, and therefore includes natural precipitation.<sup>39</sup> The WUE (in units of kg m<sup>-3</sup>) was calculated using the method described by James<sup>40</sup>:

$$WUE = \frac{Y (\text{Kg/ha})}{AW (\text{m}^3/\text{ha/season})} \quad (1)$$

Where  $Y$  represents the yield and  $AW$  represents the applied water during the growing season.

### Predicted and measured $ET_r$

Lysimeters were used to measure  $ET_r$  of alfalfa and  $ET_c$  of potato for the three consecutive growing seasons. Reference  $ET_r$  values were measured by the lysimeters for the growing seasons utilize the soil water equilibrium equation (2), as follows:

$$ET_c = I + P - D - R \pm \Delta S \quad (2)$$

Where  $\Delta S$  is the change in soil-water storage (mm) between planting and harvesting dates,  $P$  represents the amount of precipitation (mm) recorded by the weather station at the site,  $I$  is the amount of applied irrigation (mm) as measured by a flow meter, and  $D$  is the amount of drainage (mm) from the bottom of the root zone. No surface runoff ( $R$ ) occurred on the experimental sites during the study seasons, as rainfall intensity is usually low. The  $K_c$  incorporates crop characteristics and averaged effects of evaporation from the soil, which is the ratio of  $ET_c$  to  $ET_r$ , and also integrates the effects of the field environment, such as ground cover, canopy properties, and aerodynamic resistance. The potato crop  $ET_c$  relates to the reference evapotranspiration ( $ET_r$ ) via the following equation:

$$K_c = ET_c / ET_r \quad (3)$$

Where  $K_c$  is the crop coefficient and  $ET_r$  is the measured reference evapotranspiration expressed in units of mm/d. The measured evapotranspiration for alfalfa ( $M-ET_r$ ) during the years 2012-2015 was compared to the predicted evapotranspiration ( $P-ET_r$ ) using the Penman-Monteith (PM) formula on a daily basis. The PM equation is a standardized estimate of the ET of 50-cm tall alfalfa; to perform the calculation, an automatic weather station was installed beside each lysimeter, from which the input parameters (temperature, relative humidity, radiation, wind velocity) for calculating alfalfa  $ET_r$  using the PM formula were collected.

## Statistical and economic analysis

The experiments used a split-plot design with three replications. Analysis of variance (ANOVA), carried out by using the SAS version 9.1 computer program.<sup>41</sup> That allowed evaluating the statistical differences between treatments in terms of locations were assigned to the main plots and crop species were distributed randomly over the sub-plots. ANOVA was assessed according to Steel<sup>42</sup> and Torrie. Economic analysis was performed using the prevailing market prices for inputs at planting and for outputs at harvest. The economic potential for irrigated potato production in the study regions was assessed from two angles: the estimated net return and the return from water use. Assessing the economic potential included estimation and comparison of average area productivities (ton ha<sup>-1</sup>), water requirements (m<sup>3</sup> ha<sup>-1</sup>), water costs (US\$ m<sup>-3</sup>), market prices (US\$ ton<sup>-1</sup>), variable costs (US\$ ha<sup>-1</sup>), economic return (US\$ ha<sup>-1</sup>), net return (US\$ ha<sup>-1</sup>), and water return (US\$ m<sup>-3</sup>).

## Results

### Analysis of measured and predicted ET

Averages of the monthly measured and predicted ET<sub>c</sub> for potato crops during the three seasons for the four locations are shown in Figures 2 and Figures 3. Figure 2 shows the variation in measured ET<sub>c</sub> among the regions and at different growth stages, ranging from a

low of 2.1 mm/d in the Eastern Province during the germination stage to a high of 12.5 mm/d in the Al-Jouf region during the flowering stage. The average measured seasonal ET<sub>c</sub> values were 5.72 mm/d, 4.42 mm/d, 5.06 mm/d, and 7.49 mm/d for the Riyadh, Qassiem, Eastern Province, and Al-Jouf regions, respectively. In general, peak ET<sub>c</sub> for potato occurred nearly 8 weeks after sowing, and during the reproductive growth stage. Similarly, as shown in Figure 3, the predicted ET<sub>c</sub> data for the same period ranges from 2.61 mm/d to 10.31 mm/d. The average M-ET<sub>r</sub> values for the alfalfa crops were 4.52 mm/d, 4.86 mm/d, 5.00 mm/d, and 4.78 mm/d (Table 4), whereas the average P-ET<sub>r</sub> values were 3.40 mm/d, 3.45 mm/d, 4.23 mm/d, and 3.66 mm/d for the Riyadh, Qassiem, Eastern Province, and Al-Jouf regions, respectively.

### Statistical analysis

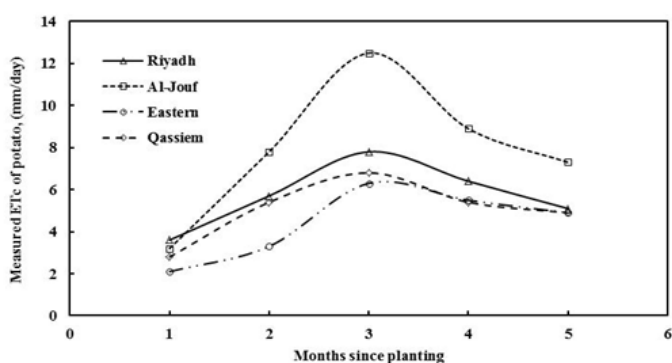
A goodness-of-fit analysis indicated that the variances among the means of the measured and calculated ET<sub>r</sub> for the potato crops in Qassiem and Al-Jouf were significant, whereas no significant differences were found for the measured and predicted ET<sub>c</sub> among the regions, implying that although there are differences in ET<sub>r</sub> within each study region, ET<sub>r</sub> is consistent between the study regions. Pearson correlation analysis indicated a powerful correlation among the means of the measured and calculated ET<sub>r</sub> within each study region, ranging from a lower of 0.97 in the Qassiem region to a maximum of 1.0 in the other three regions, as illustrated in Table 5.

**Table 4** Averages of measured and predicted ET<sub>r</sub> for alfalfa crops in the four regions

Month	Riyadh		Qassiem		Eastern		Al-Jouf	
	M-ET <sub>r</sub>	P-ET <sub>r</sub>	M-ET <sub>r</sub>	P-ET <sub>r</sub>	M-ET <sub>r</sub>	P-ET <sub>r</sub>	M-ET <sub>r</sub>	P-ET <sub>r</sub>
	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
1	3.5	2.65	3.3	2.31	3.5	2.93	3.1	2.34
2	4.6	3.46	3.2	2.21	3.6	2.92	2.9	2.2
3	6.2	4.59	4.3	3.1	3.9	3.81	4.1	3.24
4	3.6	2.64	5.8	4.11	6.5	4.99	5.8	4.38
5	4.7	3.64	7.7	5.51	7.5	6.48	8	6.15
Avg.	4.52***	3.40***	4.86 n.s	3.45***	5.0 n.s	4.23 n.s	4.78***	3.66***

M, Measured; P, Predicted - n.s. differences are not significant at 0.01 level. –

\*\*differences are significant at 0.01 level, \*\*\*differences are not significant at 0.001 level

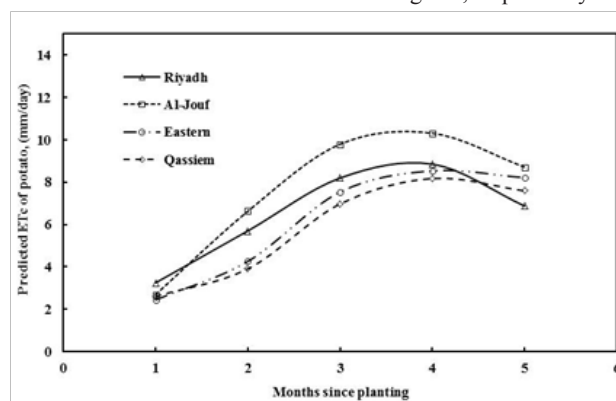


**Figure 2** Measured ET<sub>c</sub> of potato for the four regions.

### Potato crop coefficient

The predicted monthly K<sub>c</sub> through the interval of study for all regions as calculated using Equation 3 is presented in Figure 4; variations in the averages of the coefficients related to the different crop development stages for the four regions over the three seasons are

plotted in the same figure. Maximum measured K<sub>c</sub> values for potato ranged between 1.12 and 1.16 for Al-Jouf and Eastern Province, respectively, whereas minimum average values ranged from 0.49 to 0.52 for the Al-Jouf and Eastern Province regions, respectively.



**Figure 3** Predicted ET<sub>c</sub> of potato for the four regions.



### Water requirements

Gross irrigation water requirements during the growing period for the four regions based on  $ET_c$  lysimeter measurements under surface irrigation practices are shown in Table 6. The highest seasonal irrigation requirement was  $11,843 \text{ m}^3 \text{ ha}^{-1}$  for Al-Qassiem, and the lowest value was  $6,712 \text{ m}^3 \text{ ha}^{-1}$  for Riyadh. Seasonal WUE averages for the four regions are also shown in Table 6.

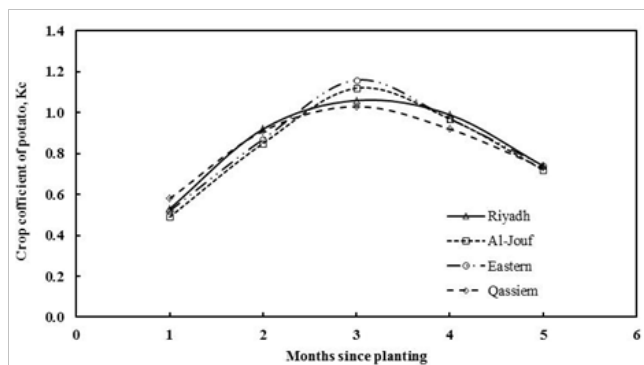


Figure 4 Variation of the averages of the Kc for potato during the growth period over three seasons.

### Water use efficiency

The WUE, which represents the relationship between crop yield and the quantity of water utilized, is presented in Figure 5. WUE can be used to ascertain the influences of the irrigation methods productivity of crops, which indicate the effects of different irrigation systems on potato crops. The highest WUE value (3.64) was measured for the Riyadh region, with the lowest observed in the Al Jouf region.

Table 6 Average gross water used and WUE

Region	Gross water used Surface ( $\text{m}^3/\text{ha}/\text{season}$ )	ET seasonal	Yield ( $\text{ton}/\text{ha}$ )	Water use efficiency Surface ( $\text{kg m}^{-3}$ )
Riyadh	6712	392	24.4	$3.64 \times 10^3$
Qassiem	11843	691	18.25	$3.15 \times 10^3$
Eastern	7130	461	17.69	$2.48 \times 10^3$
Aljouf	8564	500	26.97	$1.54 \times 10^3$

Table 7 Economic potential of irrigated potato production in the four regions

Region	Average Production $\text{Ton ha}^{-1}$	Average Water Cost $\$ \text{m}^{-3}$	Average Market Price $\$ \text{ton}^{-1}$	Water Requirements $\text{m}^3 \text{ ha}^{-1}$	Average Var. Costs $\$ \text{ha}^{-1}$	Average Return $\$ \text{ha}^{-1}$	Average Net Return $\$ \text{ha}^{-1}$	Average Water Return $\$ \text{m}^{-3}$
Riyadh	24.4	0.06	409.3	6712	5387.5	9989.1	4601.3	1.49
Qassiem	18.3	0.06	466.7	11843	1089.6	8516.8	7426.9	0.72
Eastern	17.7	0.06	266.7	7130	3852.3	4717.6	865.3	0.67
Al Jouf	27	0.07	186.7	8564	2831.3	5033.8	2202.7	0.59
Average	21.8	0.06	332.3	8562	3290.3	7064.3	3774.1	0.85
Max	27	0.07	466.7	11843	5387.5	9989.1	7426.9	1.49
Min	17.7	0.06	186.7	6712	1089.6	4717.6	865.3	0.59

Source: calculated in the study, 2014

### Economic analysis

Economic data for irrigated potato production in the different regions over the 3-year period are shown in Table 7. The average water-return productivity ( $\text{US\$ ha}^{-1}$ ) was calculated by estimating the actual harvestable yield. It is clear from this table that the economic potential of irrigated potato production is highest in the Riyadh region, followed in order by the Qassiem, Eastern Province, and Al Jouf regions. The maximum average water return was also observed for the Riyadh region, with the minimum value occurring in Al Jouf. The average net return for the irrigated potato crop was estimated to be approximately  $\text{US\$}4,601.30 \text{ ha}^{-1}$ ,  $\text{US\$}7,426.90 \text{ ha}^{-1}$ ,  $\text{US\$}865.30 \text{ ha}^{-1}$ , and  $\text{US\$}2,202.70 \text{ ha}^{-1}$  in Riyadh, Qassiem, Eastern Province, and Al Jouf, respectively. It is notable that the minimum water return over the three growing seasons occurred in Eastern Province, whereas the maximum occurred in Qassiem.

Table 5 Statistical analysis of measured and predicted  $ET_c$

Region	Mean, predicted $ET_c$	Mean, measured $ET_c$	Pearson correlation coefficients
Riyadh	6.58	5.72	0.99
Qassiem	5.85	4.42	0.97
Eastern	6.2	5.06	0.98
Al-Jouf	7.63	7.94	1
Average	6.57	5.79	0.985
Max	7.63	7.94	1
Min	5.85	4.42	0.97

Source: calculated in the study, 2014.

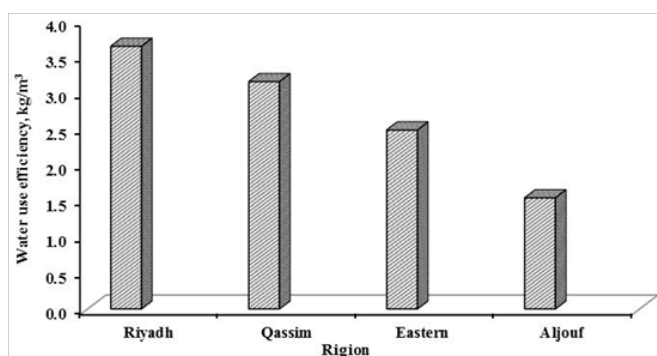


Figure 5 Water-use efficiencies of potato for the four regions.

## Discussion

### Analysis of measured and predicted ET

Figure 2, shows that there were significant variations in  $ET_c$  were detected between regions, most likely due to differences in their geographic location and topographies, especially elevation. In addition, meteorological conditions, such as radiation, wind speed, humidity, and temperature, greatly influence evapotranspiration. Therefore, it is necessary to reduce water losses due to increases in the evaporative demands in these arid regions, especially during critical periods. The differences in  $ET_c$  might be ascribed to daily variations in the maximum and minimum temperature resulting from different microclimates across the three seasons, and due to differing levels of relative humidity. The impact of climate variability on agricultural production is important at local, regional, national, and global scales.<sup>43–45</sup> The average monthly  $ET_c$  was relatively low in early growth stages but increased gradually, peaking during the flowering stage before dropping again at harvest. This might be due to  $ET$  characteristics during the initial stages, which are predominantly in the form of evaporation and affected by the evaporative power of the atmosphere, the magnitude of wetting events, and the time interval between wetting events. This result is in close agreement with that for the Eastern Province. Al-Omran and Shelby (1992) estimated total crop water requirements of potatoes at approximately 5.2 thousand  $m^3/ha$ . Similar findings were also reported by Al-Ghobari<sup>10</sup>, who estimated a water requirement in Najran of approximately 4.16 thousand  $m^3/ha$  for potatoes, which accords with the results of Sahin et al.,<sup>28–30</sup> Figure 3 shows that the average predicted seasonal  $ET_c$  rates of the four regions are similar to the measured values, with some minor divergences. Maximum  $ET_c$  occurred in the Eastern Province, with the minimum observed for the Riyadh region. The divergence between the measured and predicted values can be attributed to the PM equation, which does not take into account several micro-climatic conditions that may affect evaporation rates. Generally, however, the trends for the predicted values are similar to those of the measured values, and appear to be consistent throughout the season. Therefore, the  $ET_i$  is a little undervalued nearly all sites, due to high evaporative request. This slight underestimate in the calculated  $ET_i$  may be due to the actuality that the system contains several experimental functions that require local calibration.

### Potato crop coefficients

Variations in the crop coefficient relating to different crop development states for the four regions are shown in Figure 4. The results indicate that the average value of monthly  $K_c$  during each season is similar but not identical in all regions. This minor variation

is justified given that the  $K_c$  consolidates crop properties and the means influence of evaporation from the soil. These averages are pertinent and extra appropriate than the  $K_c$  calculated on a daily time step utilize a separate crop and soil coefficient Characteristics.<sup>46</sup> Nevertheless, this variation is expected, given that  $K_c$  is affected by all factors influencing soil water status, such as the type and frequency of irrigation,<sup>47–49</sup> climate, soil characteristics, and agronomic practices.<sup>50</sup> Previous studies have shown that the interaction between management practices and climate influences  $K_c$  for initial, middle, and late stages of crop growth. In general,  $ET_i$  and the corresponding  $K_c$  are unique to a given crop, its microenvironment, and its geographic location.

### Water requirements

As can be seen in Table 5, gross water requirement varied among the regions, which may be due to the differences in daily air temperatures and relative humidity, in addition to dissimilar irrigation efficiencies and management practices between the regions. A more comprehensive understanding of how water requirement relates to geographic location and micro-climates is needed.

### Water use efficiency

Water-use efficiency was highest in the Riyadh region, most likely due to the higher yields achieved in this region and to the volume of irrigation water used, whereas WUE was lowest in Qassim. Several factors affect crop yield in addition to the amount of water added, such as soil fertility, texture, and manure content. As such, our experiments clearly demonstrate the importance of the addition of appropriate amounts of irrigation water, as high levels of production can be attained even with reduced irrigation. Hence, there is an urgent need for improving crop WUE in order to ensure sustainable use of limited water resources.

### Economic Analysis

The potential for an economically viable potato production industry is highest in the Qassim and Riyadh regions (Table 6). Estimated net returns for potato production are influenced mainly by fluctuations in the average variable costs and the prevailing average market prices in the study regions, a trend that was similar between years. This is perhaps due to fluctuations in the demand and supply of tubers during the early growing season, with higher demand and lower availability driving up market prices. The average net-return ratio is a critical factor in crop selection and the choice of planting season; farmers in Riyadh, for instance, have switched to growing potato crops during mid-October in order to fetch a better return. Similar results were reported by Kumar et al.,<sup>51</sup> for producers of okra, whereas Pereira et al.,<sup>37</sup> found that the performance of the proposed model, the estimated values of tuber yield was compared with observed productivity data under irrigation conditions for the studied sites.<sup>52</sup>

## Conclusion

This research was aimed for determination of exact plant water usage or crop evapotranspiration ( $ET_c$ ) and crop coefficients ( $K_c$ ) for potato crop. Here, we examined the  $ET_c$  of the potato *Solanum tuberosum* L. and the  $ET_i$  of alfalfa to determine the crop coefficient,  $K_c$ , of potato crops grown in four distinct geographic and climatic regions of Saudi Arabia with the aim of creating a framework for systematic scientific assessments of the water requirements of crops so as to avoid the underestimation or overestimation of irrigation requirements. A better understanding of appropriate levels of water use through measurements of actual evapotranspiration is necessary

to achieve sustainable development and environmentally sound water management in arid regions such as Saudi Arabia. The irrigation requirements of potato were predicted using the PM model, with the average  $K_c$  values for the three growing seasons estimated to be 0.85, 0.83, 0.85, and 0.83 for the Riyadh, Qassim, Eastern Province, and Al Jouf regions, respectively. The seasonal  $K_c$  values varied from 0.49 to 1.16 for potato. Our results presented that  $K_c$  values can be different from one region to the other. It is assumed that the different environmental conditions between regions allow variation in variety selection and crop developmental stage which affect  $K_c$ . We assume that the development of regionally based and growth stage specific  $K_c$  helps in irrigation management and provides precise water applications for this region. In conclusion the development of regionally based  $K_c$  helps tremendously in irrigation management and furthermore provides precise water applications in those areas where high irrigation efficiencies are achieved by surface irrigation. Therefore, from these results, it is concluded that the lysimeter method can be recommended for computing evapotranspiration ( $ET_c$ ) and crop coefficients ( $K_c$ ) for all areas in the case studies, measurements of the water, which provide more reliable measurements.

Water requirements for potato crops varied over the course of the growing season due to variations in geography and climatic conditions. The measured  $ET_c$  showed acceptable agreement with the data obtained from the lysimeters with a few exceptions; in many cases, corrections are unnecessary. Finally, our results emphasized the importance of efficient allocation of irrigated potato production to regions having comparative advantages in the Kingdom, such as Al Jouf and Qassim. It is expected that adoption of a new openness in considering all costs and benefits, and more precise use of terms could lead to much improved. The consideration of economic water productivity indicators shows to be of relevance when analyzing improvements in irrigation systems and management at farm and project scales. Case studies are shown to illustrate the use of these economic water productivity indicators in practice. It may be expected that their adoption will provide for a better understanding of water conservation and saving. Inevitably this could lead to better understanding of water performance and productivity by farmers and the public and by government and water agency decision makers. However, further research is warranted using lysimeter method to optimize the irrigation strategies. This will lead to appreciable saving of water in potato production considering the large area it enjoys worldwide.

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## Conflicts of interest

The author declares there is no conflict of interest.

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