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Applicability of Crop-R method for irrigation scheduling of cultivated potato in sandy soil comparing with climatological-FAO approach

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Abstract

Agricultural water management is a key factor for sustainable production in semi-arid and arid regions. Precise irrigation is a main strategy for the agricultural water management, where using quick models for irrigation scheduling is an effective way for increasing water use efficiency by crops. This study compared the effectiveness of two irrigation scheduling techniques i.e., ETC values calculated by FAO approach and Crop-R method on potato crop (*Solanum tuberosum* sp.) grown in sandy soil during the season 2019/2020. Results showed that Crop-R method was more effective than the FAO method in increasing water use efficiency (WUE) by 24%, through maximizing the tuber yield by 3.3% and the applied irrigation water by 7.1%. Moreover, the number of irrigation events decreased from 57 in FAO method to 53 in Crop-R method, which means less energy consumption as well as less CO2 emissions. It is worth mentioning that the Crop-R method saved 675 m3 ha-1 of the irrigation water as compared to the other method. These results support the efforts of agriculture sustainability and water saving in semi-arid and arid regions through irrigation scheduling by the Crop-R method due to its positive effect on crop yield and WUE.

Keywords: FAO method; Crop-R method; wadi al-natrun; irrigation scheduling; soil moisture sensors

Full length article **Corresponding Author*, e-mail: i.fatouh@agri.zu.edu.eg

1. Introduction

More than 40% of the consumed food worldwide is produced through irrigated agriculture in just one fifth of the total cultivated land [1]. In this respect, potato is a food-security crop, ranking as the fourth important crop after main grain crops (rice, wheat and maize) [2]. The agricultural irrigation withdraws more than two thirds of the global fresh water and on average, 85% of the human water consumption [3,4]. Nationally in Egypt, most of fresh water is used in the agricultural sector, accounting for 85 % of the total water resources (55.5 billion m-3 yr-1) [5]. Given the population growth and the richer diets, the energy and food demand are projected to grow considerably in the coming decades, acquiring a significant extension in the irrigated croplands and an increment in the irrigation water consumption [6]. Moreover, the water demand is expected to have severe conflicts among natural ecosystem, social economy and agricultural production sectors, especially in semi-arid and arid regions [7,8], driven by the projected drought risks and the arising irrigation variability [9]. Here, Egypt is an ideal region for such conflicts, considering the limited land, and water resources and the location in semi-arid region accompanied by accelerated increase in the population and food demand. The Western Desert of Egypt is a key area for such agricultural expansion, which represents about two thirds of the Egyptian territory. It includes different areas (five Oases in the Western Desert including Siwa, Bahariya, Farafra, Dakhla, and Kharga and three depressions including Fayoum, Wadi El-Natrun, and Qattara) that could be used for agricultural purposes on the basis of their land suitability and availability of water resources [10]. Surface irrigation is the common irrigation system used in Egypt, which is not efficient and loses a considerable amount of water. Additionally, it might not be suitable for certain crops of low water requirements. Therefore, precise irrigation is a key factor for optimizing potato production in these regions through an effective irrigation management and scheduling (right amount at a right time) as it is one of the water sensitive crops [11].

Scheduling of irrigation at the critical stages would increase crop productivity and water use efficiencies of potato [11]. Here, there are numerous approaches that can be used to schedule the irrigation, which differ in precision, time and costs [12,14]. These approaches include pan evaporation [15,16], crop growth stage basis [17-19], soil moisture basis [20,21], soil water potential [19], leaf water potential [22], stress day index (SDI) [23], and climatic approach (evapotranspiration basis) [24]. Although the field measurements-based approaches are accurate, climatic approaches are commonly used to compute evapotranspiration (ET) using weather data owing to the difficulty of obtaining accurate field measurements with consuming much time and efforts. Semi empirical and empirical equations have been introduced using meteorological data for calculating the reference evapotranspiration such as the Food and Agriculture Organization (FAO 56) Penman–Monteith (P-M) [25], Priestley-Taylor method and the Hargreaves method. Based on the previous studies, P-M equation was recommended as the sole standard method by FAO to calculate evapotranspiration. It incorporates both soil, physiological and meteorological parameters and it has been widely used as a result of intrinsic rationality and reliability [26,29]. Another type is the use of soil moisture sensors that allow to measure moisture content at a very short intervals of time. An automatic irrigation system based on sensing technology is required to reduce the costs and to give uniformity in water application across the field [30]. Soil moisture sensing has allowed low-volume and high-frequency irrigation water supply for different vegetable crops and the reduction of workforce [31]. It was proved that irrigation scheduling based on real time soil moisture measurement improved yield and water-use efficiency of crops more than irrigation scheduling based on climatological approach [32].

Few studies have tested the use of soil moisture sensing for irrigation scheduling as compared with the climatological approach, of which none of them has quantified the applicability of both approaches with potato crop in extreme arid region such as Wadi El-Natrun area. Consequently, the aim of this work was to compare two irrigation-scheduling techniques (Crop-R method and ETC method) in terms of water use efficiency, yield productivity and yield components of potato crop grown in a newly reclaimed soil under arid climatic conditions. This study contributes substantially to the efforts of optimizing water productivity and conservation of global water resources for sustainable agricultural production.

2. Materials and Methods

2.1. Experimental location and climatic conditions

The experiment was carried out in Wadi El-Natroun region, Egypt (30°17'59.8"N 30°01'39.9"E), which is located in a narrow depression at West of the Nile Delta with a total extension of about 281.7 km2 (i.e. 28170 ha). This is a promising area for possible reclamation and agricultural utilization due to its location (near Cairo) and the presence of suitable groundwater for irrigation [33]. Center pivot irrigation system is the common irrigation system in this area. The origin of the underground water in Wadi El-Natroun is seepage from the Nile River and the salinity of the irrigation water is 1.55 dSm-1, which is suitable for potato growth [34]. Wadi El Natroun is an extremely arid region with mean annual rainfall, evaporation and temperature of 41.4 mm, 114.3 mm and 21°C, respectively [35]. More details about the climatic conditions over the crop growth season are shown in (Table 1). The experimental site with two adjacent sites where both methods of irrigation scheduling were applied is presented in (Figure 1).

Table 1: Meteorological data of the experimental site during the growth season 2019-2020

Climatic factors	Precipitation (mm)	T max. (°C)	T min. (°C)	Relative humidity (%) (Max)	Evapotranspiration (ET) (mm day-1)	Solar Radiation, (W m-2)	Wind Speed (m s-1) (Max)
September	0.0	37.5	17.1	53	4.8	205.184	3.0
October	0	38.6	13.2	56	3.6	138.568	2.8
November	0.4	25.8	6.7	70	2.6	11.959	2.6
December	0	24.6	5.2	87	2.2	100.408	4
January	0	20.5	3.7	79	2.4	113.43	5.4

Note: The weather station is located inside the center pivot, at a height of one meter and half over the plants. T max. and T min. are the maximum and minimum temperatures during the month, respectively.

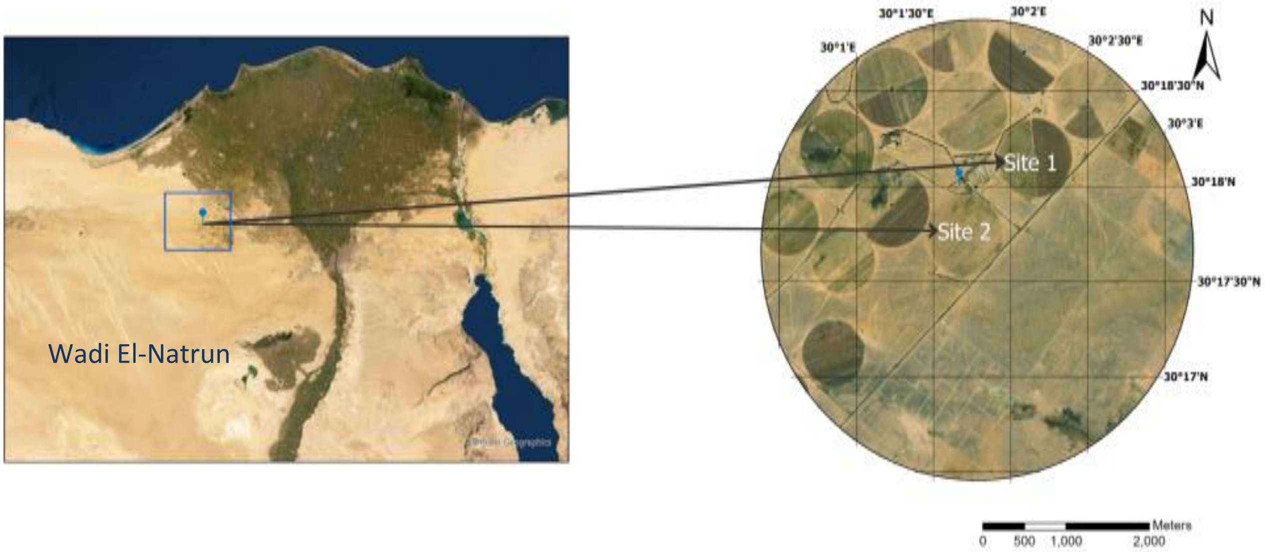

Figure 1: Location of the study area.

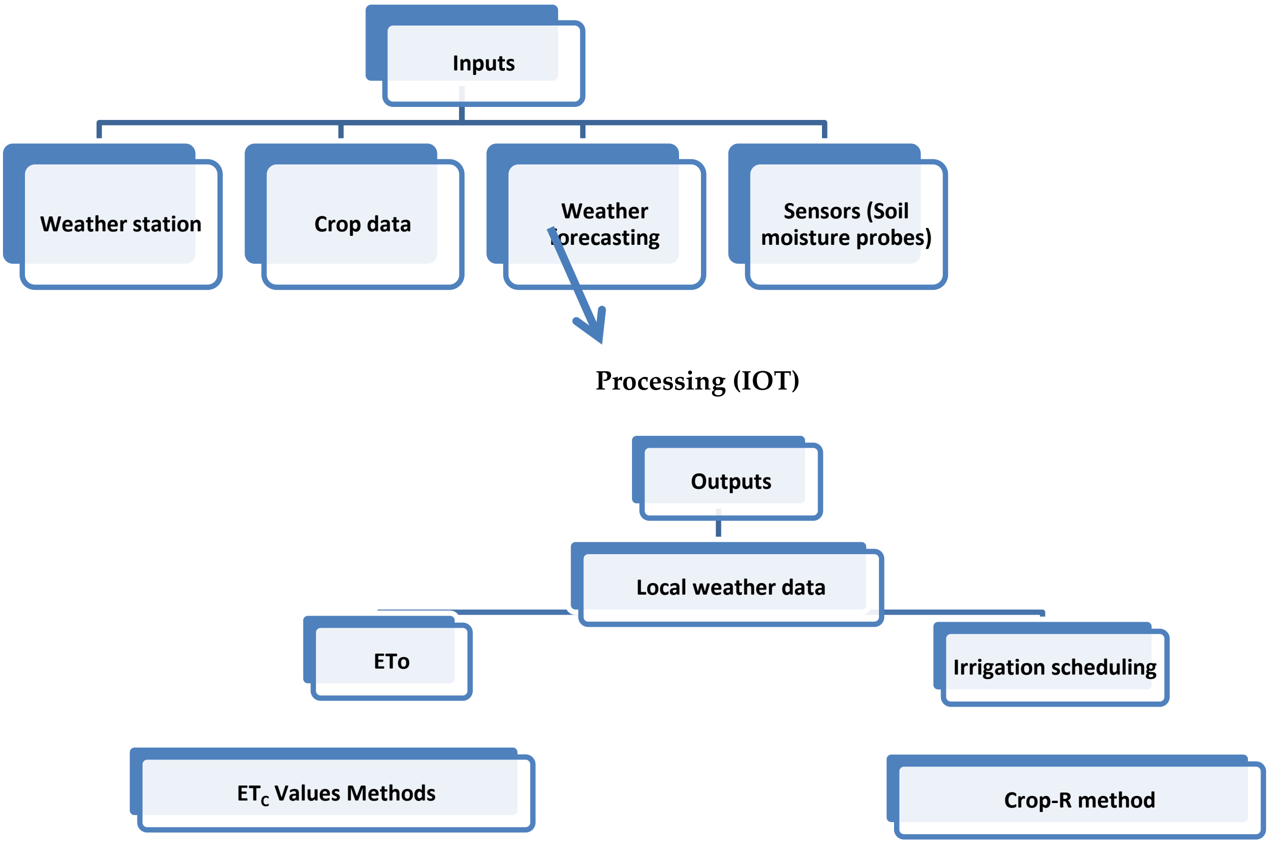

Figure 2. Flowchart of the steps through the irrigation system.

2.2. Site description and the agronomic practices

The trial was carried out in two adjacent sites, each one representing half of the area covered by the center pivot with an extension of 23.9 and 13.4 ha for the sites 1 and 2, respectively. The Crop-R method was applied in site 1, while the FAO Penman–Monteith method was performed in site 2.

In each site potato crop (*Solanum tuberosum*, Santana) was cultivated with tuber seed of 45-55 mm size. Brief description of agricultural practices for potato are reported in (Table 2). Fertilization program of potato crop was applied according to the FAO guidelines as follows: 80-120 kg N ha^{-1}, 50-80 kg P ha^{-1} and 125-160 kg K ha^{-1} [36].

Table 2: Brief description of potato agricultural practices performed in both sites.

Agricultural practice	Description
Soil preparation	Ploughing with Packer on 15/09/2019
	Rotary harrowing on 28/09/2019
	Ridge (The soil was ridged to 25cm above the tubers and the distance from top of the ridge to the bottom of the furrow was around 34 cm) on 12/10/2019.
	Dammer diker on 15/10/2019
Crop planting	Planting date on 28-29/09/2019
	planting distances (18.5 cm)
	The number of potato tubers used for planting (6 tubers/ m^2)
	Seed rate (3480 kg ha^{-1})
	First possible harvest (Jan. 14, 2019)
	Previous crop (Spring barley)

2.3. Irrigation scheduling

The irrigation scheduling was performed under the center pivot using two approaches as following:

2.3.1. Crop-R method

The Crop-R method is an online platform offering GIS-based crop-recording applications on the web (Figure 2), smartphones and tablets. The calculation of irrigation water is based on the obtained data from soil moisture sensors named as Terrasen (Crop-R Method, Dacom company, Nertherlands), which continuously monitors the volumetric soil water content (θv) over several depths in the root zone. The sensor TerraSen devices were installed the potato row between two healthy plants at soil depths of 0–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.4 and 0.4–0.5 m. Once the experiment began, the θv was measured daily up to a depth of 0.5 m at 0.1 m intervals in each of the irrigation treatments. Based on the data delivered from the soil sensors, the Cop-R method gave a decision about what is called refill point, which is determined on Management Allowable Deficit or Depletion (MAD). The latter is the percentage of the available water in the crop root zone that can be depleted by the plant without suffering water stress before the next irrigation. The MAD is primarily a function of crop type, soil type, management practices, and climate. For high cash value crops, the MAD may be 30% or less to maintain a high productivity level [37].

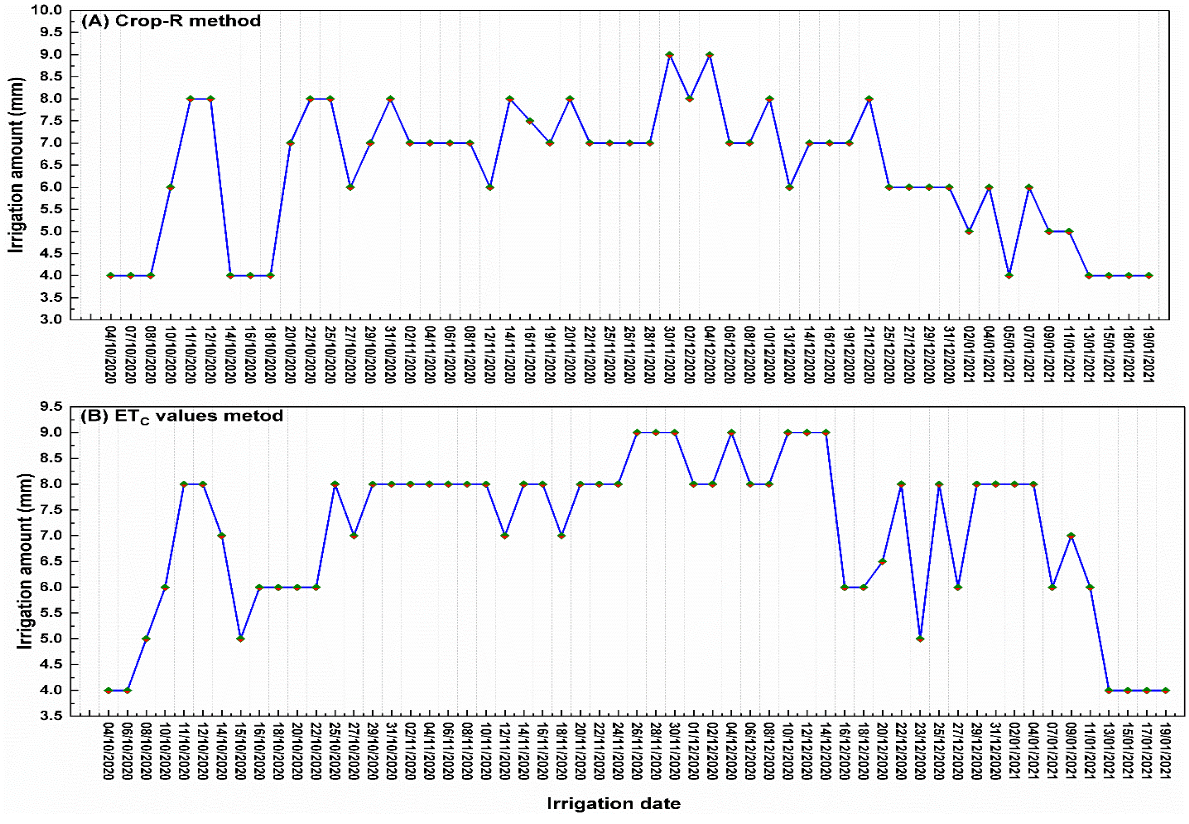

Figure 3: Irrigation scheduling by Crop-R method (A) and ETC values method (B).

2.3.2. The climatological FAO method

The crop water requirements (CWR) could be determined quickly using the climatic conditions based on the FAO Penman–Monteith method to predict reference evapotranspiration (ETo) and crop evapotranspiration (ET_C) [26,29]. This method was applied in the site 2 using climatological data from the weather station installed within the study area. The meteorological data were first used by Crop-R method to calculate the daily reference evapotranspiration rate (ETo) (Figure 2) [25], which was coupled with crop coefficient (Kc) to calculate ET_C as follows:

$$ET_C = ET_0 \times Kc$$

The Kc values of the crops used in this study were obtained from FAO bulletin No. 56 and some values were adjusted according to the results of actual field trials in Egypt. The Ks, indicating response of crop transpiration to the water stress, was added to the Kc when calculating the CWR [38,39].

Crop evapotranspiration includes the water required by crop for its physiologic functions, but this is much smaller than evaporation. Hence, ET_C is often taken as the consumptive irrigation requirement (CIR). The net irrigation requirement (NIR) is defined as the amount of irrigation water required to meet the consumptive requirement of crop as well as other needs such as leaching, pre-sowing and nursery water requirement (if any). Thus, the NIR is given by the following equation:

$$NIR = CIR + LR + PSR + NWR$$

Where LR is the leaching water requirement, PSR is the pre-sowing water requirement, NWR is the nursery water requirement. The leaching requirements were calculated according to the following equation:

$$LR = \frac{EC_{iw}}{5(EC_e) - EC_{iw}}$$

Where, ECe is the salt concentration that causes 10% yield reduction. The ECiw is the salt concentration of the irrigation water. The max ECe is the maximum tolerable electrical conductivity of the soil saturation extract for a given crop. The crop is moderately sensitive to soil salinity with a 100% yield decrease at ECe of 10 dSm^{-1}.

Field Irrigation Requirement (FIR) is defined as the amount of water required to meet the net irrigation requirements plus the amount of water lost as surface runoff and through deep percolation. Considering a factor n_a called the water application efficiency or the field application efficiency, which accounts for the loss of irrigation water during its application over the field NIR, the FIR is calculated as follows according to:

$$\text{FIR} = \frac{NIR}{n_a}$$

The maximum interval between two irrigations was 2 days based on the water holding capacity, root depth, allowable depletion and daily ET. These irrigation frequencies are in line with those suggested by FAO for potato crop grown in sandy soils.

2.4. Field measurements and laboratory analyses

2.4.1. Crop parameters

The growth and development of the potato were monitored once per week to determine the growth stage of the crop using the Biologische Bundesanstalt, Bundessortenamt and Chemical industry scale, BBCH [40]. From planting to harvesting, the length of the plant, growth stage and BBCH were recorded weekly as shown in (Table 4). In BBCH scale, the BBCH equals to 7 corresponds in planting, 9 in emergence, 40-51 in onset of flowering and tuber formation, 91 in onset of senescence and 49-95 in harvest stages. It indicates the critical stages in the life of the crop in order to optimize agricultural management for irrigation, fertilization and pest control. A 100% of emergence of potato crop was observed at October 24th 2019 for the experiment based on Crop-R method whereas for the other method was at October 26th 2019.

When 90% of the crop shoots have dried or their color has changed to pale yellow, they were cut, removed and burnt to control diseases. The tubers were left in the ground for 15 days before collection [41]. The harvest was carried out mechanically on 24th January and the yield was measured in Mg per hectare (Megagram, Mg =1000 kg).

Water use efficiency is calculated using the following equation [42]:

$$WUE = \frac{Y}{ETc}$$

Where, WUE is the water use efficiency in kg m^{-3}, Y is the yield kg m^{-2} and ET_C is the evapotranspiration of a crop (mm).

2.4.2. Soil parameters

The soil texture class for both sites up to 0.40 m depth was sandy as shown in (Table 3). Fifty soil samples per each site were collected at a depth of 0.40 m and mixed well to have one composite soil sample. The samples were air dried and sieved at 2 mm mesh to perform the soil physical and chemical analyses. Soil texture was determined according to the international pipette method [43], and the soil moisture properties were measured according to Baruah and Barthakur [44]. Soil pH was measured using a glass electrode in soil suspension (1:2.5), and electrical conductivity (EC) was measured in soil paste extract using EC meter according to McGeorge [45]. Soluble ions were measured as described in Jackson 1973. Available macro and micronutrients as well as available nitrogen (NH_4-N and NO_3-N) were extracted with KCl (2 N). Nitrogen was determined in the extraction with steam - distillation procedure using MgO - Devarda alloy (it is an alloy of aluminium (44%–46%), copper (49%–51%) and zinc (4%–6%) according to Bremner and Keency methods [46]. The available phosphorus content (P) was extracted and measured calorimetrically using the ascorbic acid method with UV–vis-NIR spectrophotometer [47]. The available potassium (K) (mg kg^{-1}) was extracted using 1.0 N ammonium acetate at pH 7.0 and determined using flame photometer method [48]. Soluble ions (Na, K, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}) were measured according to [49].

Table 3: Soil physical and chemical analysis of both sites

Soil property	Site 1 (CROP-R)	Site 2 (ETc values)	Site 1 (CROP-R)		Site 2 (ETc values)
Physical properties					
Clay (g kg^{-1})	23	4.3	Cl	21.5	20
Silt (g kg^{-1})	7	9.3	SO_4	5.0	6.5
Sand (g kg^{-1})	970	986.4	Ca	7.3	5.5
Soil texture class	Sandy	Sandy	Mg	4.3	5
Soil moisture properties			Na	14.4	15.2
Saturation percentage (SP) (%)	30.25	30.41	K	1.0	1.3
Field Capacity (FC) (%)	15.79	15.34	Available Nutrients (mg kg^{-1})		
Wilting point (WP) (%)	7.43	8.18	N	186	144
Chemical properties			P	15.36	21.76
pH (Suspension, 1:2.5)	7.90	7.83	K	187.6	190.9
EC, dSm^{-1} (Soil paste)	2.7	3.4	Mn	3.25	2.40
$CaCO_3$ (%)	2.97	1.98	Zn	1.06	1.23
Soil organic matter (%)	0.39	0.53	Fe	4.07	3.31
Soluble Ions (cmole$_c$ l^{-1})			Cu	0.99	0.96
CO_3	0.0	0.0			
HCO_3	0.5	0.5			

Soluble ions were determined in the extract of the soil paste.

Table 4a: Phonological growth stages and BBCH-identification keys of the potato for Crop-R and ET_C Values

Soil property	Site 1 (CROP-R)	Site 2 (ETc values)	Site 1 (CROP-R)		Site 2 (ETc values)
Physical properties					
Clay (g kg^{-1})	23	4.3	Cl	21.5	20
Silt (g kg^{-1})	7	9.3	SO_4	5.0	6.5
Sand (g kg^{-1})	970	986.4	Ca	7.3	5.5
Soil texture class	Sandy	Sandy	Mg	4.3	5
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$CaCO_3$ (%)	2.97	1.98	Zn	1.06	1.23
Soil organic matter (%)	0.39	0.53	Fe	4.07	3.31
Soluble Ions (cmole$_c$ l^{-1})			Cu	0.99	0.96
CO_3	0.0	0.0			

HCO_3	0.5	0.5			

Table 4b: Phonological growth stages and BBCH-identification keys of the potato for Crop-R and ET_C Values

Date	Crop-R			ETc values		
	Growth Stage	Crop height (cm)	BBCH §	Growth Stage	Crop height (cm)	BBCH*
28/9/2019	Planting date		07 *	Planting date		07*
24/10/2019	0	10	09	0	8	09
31/10/2019	1	18	11	1	17	11
7/11/2019	1	32	15	1	32	15
14/11/ 2019	1	42	19	1	40	19
21/11/2019	3	48	39	3	50	39
28/11/2019	5	52	51	5	54	51
5/12/2019	6	54	65	6	56	65
12/12/2019	7	56	71	7	56	71
19/12/2019	7	56	75	7	56	75
26/12/2019	8	61	85	8	56	85
02/1/2020	8	---	89	8	---	89
9/1/2020	9	---	91	9	---	91
24/1/2020	Harvest date		95*	Harvest date		95*

BBCH§ is Biologische Bundesanstalt, Bundessortenamt and Chemical industry scale.
The 07* refers to the planting date and 95* refers to harvest date according to BBCH.

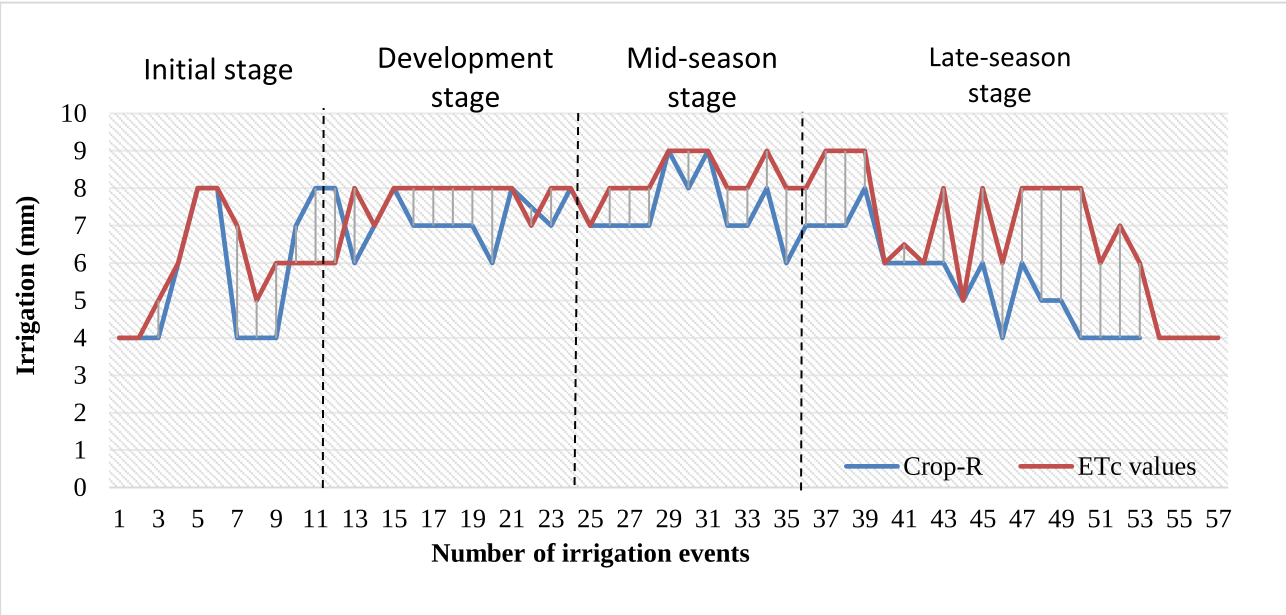

Figure 4: Crop water requirements of irrigation events in ET_C values and Crop-R methods.

3.2. Crop parameters and the water use efficiency (WUE)

The plant height increased by 7% from 56 cm when scheduling the irrigation by ET_C values method to 60 cm in the Crop-R method (Table 7). Similarly, the irrigation schedule by the Crop-R method maximized the tuber yield of potato crop (33.56 Mg ha^{-1}) by 3.3% higher than that of ET_C values method (34.69 Mg ha^{-1}) (Table 7). Considering the above results and the savings of irrigation water, the irrigation schedule by the Crop-R method resulted in augmenting the WUE by 2 kg m^{-3} greater than the ET_C values method (Table 7).

Table 5: Irrigation scheduling through the Crop-R method

Crop Stage (days)	Period	Number of irrigation events	Crop water requirements, CWR (mm)
Initial stage (1 - 25)	4/10 – 27/10	13	75
Development stage (25- 55)	29/10- 27/11	14	100.5
Mature stage (55- 95)	28/11- 25/12	13	96
Late-season stage (95- 125)	26/12- 19/01	13	65

Total		53	336.5

Note: The irrigation before planting was of 225 mm on 25/09/2020
Stage* was set according to FAO (2002)

Table 6: Irrigation scheduling through the ET_C values method.

Crop Stage (days)	Period	ETo§ (mm)	Kc	Number of irrigation events	CWR (mm)
Initial stage (1 - 25)	1/10 – 27/10	113	0.45	14	86
Development stage (25- 55)	28/10- 24/11	118	0.75	13	110
Mature stage (55- 95 day)	25/11- 29/12	93	1.15	19	148
Late-season stage (95- 125 day)	30/12- 19/1	57	0.85	10	60
Total				56	404

Note: The irrigation before planting was 225 mm at 25/09/2020.
§ ETo is th reference crop evapotranspiration (mm).

Table 7: Differences between ET_C method and Crop-R method

Parameter	ET_C method	Crop-R method
Irrigation events	57	53
CWR (mm)	404*	336.5
(CIR)§	295	---
NIR (mm)	520	---
Total water requirements (mm)	629 (FIR) §	561.5
Yield (Mg ha^{-1})	33.56 B	34.69 A
Water use efficiency (kg m^{-3})	8.31	10.30
Maximum plant height (cm)	56 B	60 A

§CIR: Consumptive irrigation requirement; §FIR: Field Irrigation Requirement.
404* is the CWR (mm) for ET_C method, which was calculated from ETc * (Kc+Ks).
The capital letters (A and B) refer to the significant at p<0.05 from one-way ANOVA.

4. Discussion

4.1. Possibility of saving the irrigation water

Lower irrigation events were scheduled by the Crop-R method as compared with the ET_C method accompanied by less irrigation amount, which indicates precise irrigation (Figures 3 and 4). In this consent, El Marazky [50] reported less irrigation requirements by wheat plant when scheduling the irrigation with intelligent irrigation system as compared with climatological-based method. This is lined with the higher actual ET_C values in the climatological-based method than that of intelligent irrigation system through applying the water at accurate time and amount [51]. It is worth mentioning that in Crop-R method irrigation decision is based on the soil moisture probe measurement, i.e. when the available water is depleted by a certain proportion, the Crop-R method starts the irrigation till the available water reaches again a given value (field capacity). Differently, in the ET_C the irrigation intervals depend on the calculation of ETo which is a function of meteorological parameters [52]. The ETC is then calculated every week and is distributed with a frequency depending on the soil type. In our case, the soil type is sandy and hence the irrigation interval is on average of 2 days.

The CWR during maturity stage was higher than other stages in the ET_C values method, but not than the development stage in the Crop-R method, indicating the need to revise the Kc values of FAO. The Kc was greater than 1, indicating that ET_C was higher than ETo only in the maturity stage corresponding to the maximum of CWR. These results especially for ET_C values are in line with those obtained by Chowdhury, *et al.* [53], who reported that the ET_C increased through the growth stages and decreased slightly at the later stages. The irrigation scheduling by Crop-R method was effective in reducing the total irrigation requirements than the scheduling by the ET_C method, agreeing well with the results of Mohammad, Al-Ghobari and ElMarazky [51], who reported 20% savings in the irrigation water when using smart irrigation technology in tomato cultivation.

4.2. Yield and water use efficiency

Achieving the higher plant height and crop yield under the irrigation scheduling by Crop-R method that that of the ET_C values method is attributable to the on-time supplement of the irrigation water through the soil moisture probe measurement, avoiding water stress or lodging [54,55]. The soil sensor helps in delivering the right amount of irrigation water to the right location and at the right time, which improves the irrigation efficiency and remarkably increases the yield production [56,57]. Under the limited water supply, the water use efficiency can be increased by controlling soil moisture stress during the development, tuber initiation and yield formation stages through restricting the water supply during the early vegetative and later stages of crop growth [58,59]. Water stress at later growth stress had little adverse effect, agreeing with the higher irrigation frequencies and amount during the mid-season growth stages through the Crop-R method (Table 5, Fig. 3). In this situation, water use efficiency could be increased by maintaining optimum soil moisture during the critical stages and sub-optimal condition during other growth stages resulted in saving of 30% in irrigation without significant reduction in the yield. On the other hand, higher WUE in the Crop-R method may also have resulted from lower irrigation frequency during the whole growth season, which is in the same consistent with [60,61], who found that low irrigation frequencies resulted in higher water use efficiency.

5. Conclusions

Sustainable agriculture depends mainly on more production with less inputs, achieving less environmental and economic costs. Precise irrigation with low labour and energy costs is a key factor of the sustainable agricultural production. Here, this study reported a significant variation in the crop water requirements of the potato crop grown in arid region was found between the irrigation scheduling by the Crop-R and the ET_C values methods. In parallel, the irrigation schedule by the Crop-R increased the plant height and crop yield significantly than that of the ET_C values method, indicating improvements in the water use efficiency by 24%. These results emphasize the advantages of irrigation scheduling by the Crop-R due to its effectiveness in saving irrigation water especially in arid regions. Moreover, it can minimize labour efforts by reducing the irrigation applications, which might affect the available soil water during the potato growing season. The results of this study can be advantageously used also by the water resource planners to promote water saving and can be used as a guide for farmers to optimize the management of irrigation.

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