

## Potato Crop Irrigation and Management: Strategies for Sustainable Water Use and Yield Optimization

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### ABSTRACT

Potato (*Solanum tuberosum* L.) is one of the most important global crops. It is the world's fourth most significant crop in terms of total production, with over 380 million metric tons of potatoes produced worldwide annually. With shallow root systems and a strong phenological response to water deficiency, scheduling and managing irrigation for potatoes is vital for tuber yield and quality. The purpose of this article is to compile and summarize the latest research findings regarding potato water needs and irrigation technologies/scheduling, soil/nutrient interactions, and biological/environmental factors that affect irrigation efficiencies. Peak water demand ranges from 500 mm to 700 mm for the potato season and occurs during tuber bulking, when the tuber's crop coefficient (Kc) value ranges from 1.05 to 1.20. Combining drip irrigation and deficit scheduling has produced up to 40% water-use savings, with minimal yield reductions, when real-time monitoring of soil moisture and evapotranspiration is used for scheduling. Enhancing water use efficiency is accomplished through soil management practices such as increasing organic matter, tillage methods, and precision fertigation. The leading edge in the precision management of potato water use includes new technologies such as IoT-enabled sensors, remote sensing, and machine-learning-based decision-making systems. This review synthesizes physiological, agronomic, and technological information into one comprehensive framework for improving potato irrigation systems under the growing global challenge of water shortages.

**Keywords:** *Solanum tuberosum*, Deficit Irrigation, Drip Irrigation, Evapotranspiration, Water-Use Efficiency, Soil Organic Matter, Precision Agriculture

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### Introduction

The potato (*Solanum tuberosum* L.) is the world's fourth-largest (by volume) food crop, produced in more than 380 million metric tons per year and cultivated on approximately 17 million hectares globally [1]. Nutritionally, potatoes are very high in carbohydrates (approx. 77%), vitamin C, and potassium, and provide a beneficial source of dietary fiber (approx. 10%). These characteristics have allowed the potato to become a staple for billions of people around the world and an important source of income for small-scale farmers in Asia, Africa, and Latin America [2]. In Pakistan and other South Asian areas of production, potatoes are primarily grown under irrigation, making water management the key agronomic driver of productivity at the farm level.

Potatoes have an inherently shallow, fibrous root system that rarely penetrates more than 30 to 40 cm below the surface under conventional tillage. Therefore, potatoes are particularly susceptible to soil water deficits and dependent on timely and accurate irrigation [3]. Unlike deep-rooted cereal crops, which can extract water from deeper horizons in the soil profile when drying occurs at the surface, potatoes will nearly always access water from the upper layers of the soil profile where evaporative losses are greatest. Potatoes can incur significant yield losses (40–70%) from even a brief period of water deficiency, especially if it occurs during tuber initiation and later bulking stages of development [4].

Agriculture currently accounts for approximately 70% of total freshwater withdrawals worldwide, and irrigated agriculture contributes disproportionately to this demand [5]. Climate change forecasts for most potato-growing areas include higher evaporative demand, changes in precipitation patterns, and an increase in the frequency of drought cycles, which exacerbate the challenge of maintaining current yield trends [6]. There is, therefore, a great need to develop integrated irrigation and management strategies that maximize the water productivity, which is the ratio of crop produced to water used. The review is a critical synthesis of existing knowledge regarding potato water physiology, irrigation technologies, soil management, factors that are important to define the efficiency of irrigation, and the future of the added discipline of precision in defining the field.

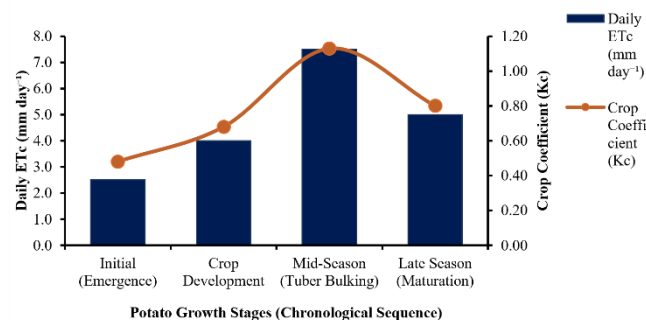
### Water Requirements and Crop Physiology of Potato Root System Characteristics and Water Uptake

The specific morphological architecture of the potato root system is a primary physiological restriction on the crop's water relations. Roots primarily arise from stolon nodes and develop a concentrated network in the top 20-40cm of the soil profile, extending laterally only 30-60cm from the central plant axis [7]. The inherently shallow distribution of potato roots thus limits the readily available water (RAW) reservoir that is available to the crop. As a consequence, potatoes require much more frequent irrigation applications than do species with deeper roots. The stomatal conductance

and photosynthetic activity of potatoes are typically inhibited once soil water depletion exceeds approximately 35 to 45% of the total available water (TAW) [8]. Additionally, stomatal regulation of potatoes is highly sensitive to both the ambient soil water potential and the atmospheric vapor pressure deficit (VPD). The physiological mechanism underlying this response is abscisic acid (ABA), a signaling molecule produced in roots under drying conditions and transported to the guard cells, which provides the physiological basis for the partial root-zone drying strategies considered in subsequent sections [9].

### Crop Coefficients and Growth-Stage Water Demand

Water demand for potatoes is most accurately quantified using the FAO-56 standard for crop evapotranspiration (ET<sub>c</sub>), which requires estimating reference evapotranspiration (ET<sub>o</sub>) and determining a dimensionless crop coefficient (K<sub>c</sub>) which varies over four separate phases of growth (K<sub>c</sub> is approximately 0.45–0.50 at emergence; increases to 1.05–1.20 at peak canopy development [mid-season, which corresponds with active tuber bulking] and then decreases to 0.75–0.85 when crop maturity occurs) [10]. Figure 1 presents the above parameters in addition to their respective daily ET<sub>c</sub> values and each of their importance as a water stress sensitive period. The mid-season stage represents the critical period for water requirement in unequivocal terms. Soil moisture content needs to be maintained at levels greater than RAW during this period, with higher allowable depletion possible during vegetative growth and later maturity. Late-season water stress, carefully managed, can increase specific gravity and enhance processibility without major loss of fresh weight [11].



**Fig. 1:** shows potato crop coefficient (K<sub>c</sub>) and daily evapotranspiration (ET<sub>c</sub>) across growth stages under semi-arid conditions (ET<sub>o</sub> ≈ 6 mm/day). The red zone indicates the critical irrigation period (tuber initiation and bulking), where soil moisture must remain above the readily available water threshold to avoid yield loss. Data from Allen et al. [10] and T et al. [11].

### Irrigation Methods and Scheduling Strategies:

### Conventional Irrigation: Furrow and Sprinkler Systems

Furrow irrigation, where water moves through channels between rows of crops, has traditionally been used extensively in potato farming in the developing world because of its low cost in terms of initial capital investment. Nevertheless, its efficiency is usually only about 50–60% efficient due to the significant amounts of water lost through deep infiltration, lateral movement, and evaporation from the water surface [12]. The efficiencies of sprinkler systems, including solid set, lateral move, and center pivot systems, where water is applied using pressure-driven nozzles, are in the range of 75–85% [13].

### Drip and Subsurface Drip Irrigation

The efficiency of water application in drip irrigation can reach between 88% to 95%, as it delivers water right into the root zone through emitter lines, thus minimizing surface and deep water loss [14]. In addition, subsurface drip irrigation reduces foliar moisture and thus minimizes a micro-environment conducive to the development of *Phytophthora infestans* (late blight), which is currently the most important biological problem affecting potatoes worldwide [15]. It has been shown that the water use efficiency of drip irrigation is higher than that of other irrigation methods since tubers produce similar or even higher yields while using less water (25% to 40%) [16].

### Deficit Irrigation Strategies

Deficit irrigation regulated (RDI) involves the application of less water than required by the fully grown crop throughout the plant growth period, where the yield penalty is acceptable, during the vegetative phase and late maturity period, while ensuring a full supply of water throughout the tuber bulking stage. Experiments carried out in semi-arid conditions show that the yield of tubers obtained using RDI represents 90–95% of the maximal yield but only using 70–80% of the water required for maximum yield [17]. The PRD technique involves irrigating alternate halves of the root zone of the plant in order to stimulate root-to-shoot signaling, resulting in water savings of 30–50% [18]. Table 1 shows comparisons between all five irrigation techniques discussed.

**Table 1:** Comparative overview of irrigation systems for potato production, including application efficiency, water savings (vs. furrow irrigation), yield impact, capital cost, and recommended deployment contexts. Sources: Sprinkle and Trickle Irrigation; Agricultural Water Management studies by Howell [19], Allen et al. [10], Shock et al. [20], Badr et al. [21], Shock and Feibert [22], and Shahnazari et al. [23].

Irrigation System	Application Efficiency	Water Saving vs. Furrow	Yield Impact	Capital Cost	Best Suited For
Furrow	50–60%	Baseline	Moderate; uneven distribution risk	Low	Small farms, limited infrastructure
Sprinkler (centre-pivot)	75–85%	15–25% reduction	High; uniform coverage	Moderate–High	Large-scale commercial fields
Surface Drip	88–95%	25–40% reduction	Equal or superior to sprinkler	High	High-value crops, water-scarce regions
Subsurface Drip (SDI)	90–95%	30–45% reduction	Superior; reduced surface disease risk	Very High	Permanent beds, precision operations
Deficit Irrigation (RDI)	Varies	20–35% reduction	90–95% of full yield maintained	Low (scheduling cost)	Semi-arid, water-restricted areas

### Soil Management and Its Interaction with Irrigation Soil Physical Properties and Water-Holding Capacity

The soil physical properties are the basic medium through which water flows and from where the roots of potatoes absorb water. The sandy soils prevalent in many of the global potato-producing regions have such properties as quick water drainage, low availability of water storage (which is usually 70 – 120 mm per metre of soil depth), and high frequency of irrigation [24]. Although sandy soils have the advantage of being highly aerated soils, hence uniform potato tubers and minimal occurrence of tuber blight, the soils require careful irrigation due to risks of drought stress and nutrient loss.

Soil organic matter (SOM) is the primary and most important adjustable factor that can influence irrigation efficiency, irrespective of the texture of the soil. A one percent increase in SOM raises plant-available water content by 1.5 to 3.5 % of volumetric basis, which means an increased period of time without the need for irrigation [25]. SOM accumulation using practices like the use of cover crops, compost (at a rate of 10 to 20 Mg ha<sup>-1</sup> per year), and conservation tillage will thus become an initial step towards better water use efficiency.

### Fertigation and Nutrient Water Interactions

The most crucial relationship between irrigation and fertilisation lies in the proper management of nitrogen in potatoes. Excessive use of irrigation leads to leaching of nitrate ions (NO<sub>3</sub><sup>-</sup>) out of the root zone area, causing both financial losses and risks of pollution. Under-irrigation hinders the nutrient intake even when the level of soil fertility is satisfactory [26]. Fertigation, a technique involving the application of the solution form of fertilisers using irrigation systems, facilitates the application of doses of nutrients such as nitrogen, phosphorus, and potassium according to phenology. It has been found that drip fertigation results in comparable crop yields with less than 20%–30% application of fertilisers, as compared to broadcasting [27]. Potassium availability during the bulking phase plays a key role in starch formation and uniform tubers.

### Factors Affecting Irrigation Efficiency in Potato:

The efficiency of potato irrigation is regulated by a complex dynamic interplay of biological, pedological, climatic, and agronomic factors. These factors must be understood when producing management plans specific to a site. The regulating factors listed in Table 2 have been summarized in a tabular format in order to present them in a more structured manner, with suggestions regarding the mechanisms of their action and the implications for their management. The choice of cultivar is one of the easiest tools to enhance water productivity. The modern varieties have deeper root systems, stomatal regulation that avoids excess tissue loss, and less reaction to short-term moisture stress than the heritage varieties [28]. The daily event of evapotranspiration demand is governed by climatic factors, of which the most important are VPD, sun radiation intensity, and wind speed, and could result in schedules that are unsuitable in rapidly changing conditions [29]. Soil salinity is a problem specific to potatoes (EC<sub>e</sub> ≈ 1.7 dS/m; yield decreases at around 12% for each unit higher), requiring careful management of salinity, both via the leaching fraction and water quality [30].

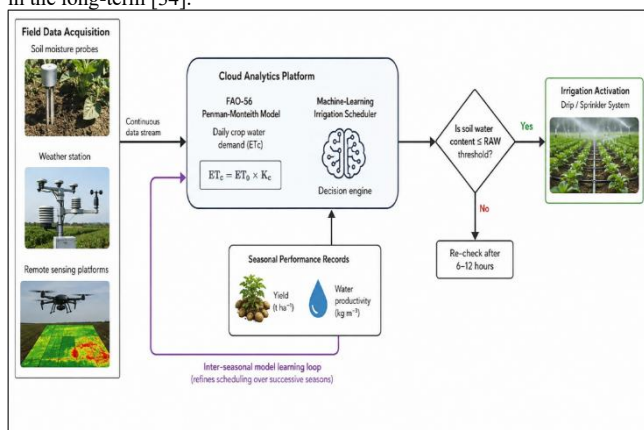
**Table 2.** Principal factors affecting irrigation efficiency in potato production, including mechanisms of action and management implications. Sources: Jefferies and Mackerron [31], Hijmans [32].

Factor	Mechanism	Management Implication
Cultivar genetics	Rooting depth, stomatal regulation, canopy architecture	Select deep-rooting, drought-tolerant varieties
Soil texture	Determines water-holding capacity and drainage rate	Amend sandy soils with compost; ensure drainage in clay soils
Soil salinity	Reduces osmotic potential; induces physiological drought	Maintain EC <sub>e</sub> < 1.7 dS/m; apply leaching fractions as needed
Climate / VPD	Drives evaporative demand; alters ET <sub>c</sub> on a daily timescale	Use ET-based scheduling adjusted to real-time weather data
Growth stage	Water sensitivity varies sharply by phenological phase	Prioritise full supply during tuber initiation and bulking
Soil organic matter (%)	Each +1% SOM stores ~1.5–3.5% more plant-available water	Incorporate compost; use cover crops;

		minimise tillage intensity
Nitrogen management	Excess N + water stimulates vegetative growth over tubers	Apply N in split doses via fertigation tied to crop demand stage

**Future Perspectives:**

Potato irrigation management is moving towards the integration of precision sensing, computational modelling, and irrigation agronomy. In the present era, an array of in-field sensors, capacitance soil moisture probes, canopy infrared radiometers, and micro-meteorological stations are enabled with IoT devices, which allows for continuous high-resolution monitoring of the soil-plant-atmosphere continuum for dynamic, real-time irrigation scheduling [33]. As shown in Figure 2, a decision support system developed using both sensor data and cloud-based ET models and machine learning algorithms trained on multi-year crop and climatic data outperforms static schedule-based systems, both in water productivity and yield stability. UAV-mounted multispectral cameras, satellite-derived spectral indices (NDVI, NDWI, crop water stress index based on temperature), and remote sensing platforms also expand precision monitoring in the spatial dimension, allowing for mapping of crop water stress at the within-field level through remote sensing data to inform variable-rate irrigation practices. Marker-assisted and genomic selection programmes are also underway in both public and private breeding programmes in both cases, studying root depth and ABA signaling sensitivity is concentrating on the genetic approach and biotechnological approach, respectively. Genome editing using programmed CRISPR-Cas can offer the possibility of improved water use traits without linkage drag in the near future, and even in the long-term [34].



**Fig. 2:** IoT-enabled precision irrigation framework for potato production integrating field sensors, cloud-based FAO-56 Penman-Monteith ETc estimation, machine-learning irrigation scheduling, and automated drip/sprinkler control with seasonal feedback learning for improved water productivity.

**Conclusion:**

Management of potato irrigation is an example of a multidisciplinary task, which combines aspects of plant physiology, soil science, hydraulics, meteorology, and data analytics. Due to its shallow root system and highly stage-specific water requirement, which can be seen on the Kc graph (Figure 1), potato irrigation requires accurate planning and scheduling based on plant physiology. The use of drip irrigation, along with deficit scheduling, in conjunction with soil moisture measurements and ET-driven decision-making tools (as shown in Figure 2), appears to be the best way to achieve a balance between yield maximization and decreased water usage. Management of soil organic matter content and fertilization through fertigation are additional factors that improve irrigation efficiency. Further progress towards more efficient water management of potatoes would involve the development of IoT-based sensing and remote sensing technologies, crop simulation modeling, and breeding of new varieties.

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