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Review

Irrigation Management in Potato (*Solanum tuberosum* L.) Production: A Review

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Abstract: Limited water resources coupled with the increase of the human population calls for more efficient use of water in irrigated agriculture. Potato (*Solanum tuberosum* L.) is one of the most widely grown crops worldwide and is very sensitive to water stress due to its shallow rooting system. With the dilemma of potato sensitivity to drought and limited available water resources restricting crop production, researchers and crop growers have been investigating different approaches for optimizing potato yield and improving crop water use efficiency under different irrigation methods. While potato response to water is affected by other management practices such as fertilizer management, the present review is focused on the potato response to water under different environments and different irrigation methods and the impact on potato quality and potato diseases. Variable results obtained from research studies indicate the non-transferability of the results from one location to another as potato cultivars are not the same and potato breeders are still making effort to develop new high-yielding varieties to increase crop production and or develop new varieties for a specific trait to satisfy consumers exigence. This review is a valuable source of information for potato growers and scientists as it is not only focused on the impact of irrigation regimes on potato yield and water productivity as most reviews on water management, but it also presents the impact of irrigation regime on diseases in potatoes, tuber specific gravity, metabolite content of the tubers and the quality of the processed potato products.



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Keywords: potato; irrigation; water productivity; disease; quality

1. Introduction

Global potato production is estimated at 370.4 million tons in about 17.34 million hectares and the production in the Americas was 45.1 million tons in about 1.54 million hectares; in Europe 107.26 million tons in 4.7 million hectares, in Oceania 1.74 million tons in 43,303 ha, in Asia 189.81 million tons in 9.30 million hectares, and in Africa 26.53 million tons in 1.76 million hectares in 2019 [1]. During the 2019 season, potato production across the United States was 21.22 million tons in about 937,300 hectares [2]. Potatoes are one of the most water-efficient crops and produce the greatest number of calories per unit of water input [3–5]. However, water management in potatoes is crucial as potato is one of the most water stress-sensitive crops due to its shallow rooting system [6–13] and the sensitivity of the potato foliage characteristics [14–17]. Sustainable water management is therefore required to optimize potato yield and water use efficiency while maintaining maximum tuber yield and quality. In this review, we explore study results in relation to water management options under rainfed, limited, and full irrigation under different irrigation methods in potato with possible impact on crop yield, water use efficiency, and the quality of the products. While other management practices might affect the outcome

of different studies and the results, we are only focusing on water management and its impacts on potatoes in this review. This review covered the period of 1953–2021 with more focus on the 1990–2021 period dataset with results of studies across the main potato production areas such as the United States, Canada, Australia, New Zealand, and Turkey. Online search engines were used for published results collection from well-known scientific journals using target keywords.

2. Potato Crop Water Use and Evapotranspiration

Potato water use and evapotranspiration have been investigated by scientists across the globe and they vary with different factors including the irrigation methods, irrigation regimes, irrigation technology, local climates, fertilizer management options, and other management and environmental factors. Potato water demand for high tuber yield depends on climatic conditions and varied from 500 to 700 mm [18]. Haverkort [19] reported that potatoes water requirement ranged from 400 to 800 mm in Peru. Dimitrov [20] found potato water use that varied from 380 to 450 mm for optimum tuber yield. Potato evapotranspiration increased with irrigation applied rate of 33 to 100% of water requirement that varied from 316 to 630 mm at Davis, California [21]. Hane and Pumphrey [22] reported potato water use of 650 mm, while for Sood and Sing [23], the potato water requirement was estimated at 350–650 mm. Ortega et al. [24] indicated that for production sustainability, it is necessary to consider seasonal irrigation amount equivalent to the range from 0.85 to 0.97 of maximum evapotranspiration while considering deficit irrigation for potato production in the province of Albacete in Spain. Karam et al. [25] found potato seasonal irrigation amount at 500–560 mm to reach the target yield under deficit irrigation. Under the Turkey climate conditions, Onder et al. [9] imposed four irrigation regimes as 0, 33, 66, and 100% of full irrigation and found that potato seasonal irrigation amounts varied from 102 to 302 mm and from 88 to 268 mm in two consecutive growing seasons. Seasonal water use by potatoes in Saudi Arabia was 1505 mm [26]. Paredes et al. [27] reported potato seasonal irrigation amount of 330 and 237 mm in two consecutive years under full irrigation treatment while it was 165 and 118.5 mm under 50% of the full irrigation treatment under the Mediterranean condition in Southern Italy with seasonal precipitation of 278 and 181 mm in the respective years.

Potato water use varies with management practices and irrigation levels [28]. Potato seasonal evapotranspiration was 413.2 ± 15 mm under drip irrigation in a loam soil while it was 362.1 ± 16 in clay soil in Valenzano, Italy [29]. Parent and Anctil [30] found a rainfed potato seasonal evapotranspiration to be 331.5 mm in 2007 in South-eastern Canada while they have reported the historical long-term average rainfed potato evapotranspiration of 563.3 mm. They reported potato maximum daily evapotranspiration of 6.5 mm/day and it occurred during the potato tuber bulking. Yactayo et al. [31] found no impact on tuber yield when applying 50% of full irrigation through partial root-zone drying compared to full irrigation in Peru. Heritage potatoes (Moe Moe (*S. tuberosum* L.) and Tutaekuri (*Solanum andigena* Juz. and Buk.)) water requirements were 610 and 611 mm while the modern potatoes (Moon-light and Agria (*S. tuberosum* L.)) water requirements were 550 and 491 mm during the 2009–2010 and 2010–2011 seasons in New Zealand, respectively [32]. In a semiarid area in Gansu Province of China, rainfed potato seasonal evapotranspiration was a function of soil surface conditions and varied from 216.5 to 249.3 mm, which seems relatively low compared to the findings of other studies [28]. Well-irrigated potato seasonal evapotranspiration was 445.2 mm in Erzurum-Turkey [33] and varied from 375.7 to 511.4 mm under arid climate in Iraq [34]. Under hot and dry climates in Spain, for the potato variety Desirée, evapotranspiration was a function of the applied irrigation amount and ranged from 150 to 550 mm [35]. Rainfed potato water use was only 195.2 mm in Turkey under the best water management [33].

Erdem et al. [36] reported the seasonal potato actual evapotranspiration (ETa) range as 445–683 mm in semiarid climatic conditions of Turkey. Seasonal actual evapotranspiration varied from 226 to 473 mm and from 166 to 392 mm when potatoes were subjected to

full irrigation and 66, 33, and 0% of the full irrigation treatment. Fully irrigated potato seasonal evapotranspiration was 484 mm in 2009 and 355 mm in 2010 while it is 376 mm and 295 mm under 50% of full irrigation and the rainfed potato evapotranspiration was 219 mm and 186 mm under the Mediterranean condition in Italy [27]. Similarly, potato seasonal evapotranspiration varied with irrigation regimes, and the well-irrigated potato evapotranspiration was 448 mm in 2007 and 411 mm in 2008 in Sicily, Italy [37]. The findings of Ferreira and Carr [35], Shock et al. [38], Onder et al. [9], and Ati et al. [34] also relate to an increase in potato evapotranspiration with irrigation regime. Aksic et al. [39] reported that potato seasonal evapotranspiration varied with irrigation depths and ranged from 288.1 to 522.1 mm with the lowest value obtained under rainfed conditions while the highest value was obtained under the well-irrigated treatment. Potato seasonal water use under different irrigation methods and rainfed conditions across different locations is summarized in Table 1.

3. Water Management in Potato

3.1. Irrigation Techniques vs. Potato Growth and Yield

Different irrigation methods such as sprinkler, furrow, surface drip, and subsurface drip irrigation were used under potato production with different results according to the local climate and soil condition with contrasting outcomes in some studies. Onder et al. [9] compared surface drip and subsurface drip irrigation coupled with four irrigation regimes as 0, 33, 66, and 100% of full irrigation and found that irrigation methods did not make significant differences in tuber yield. However, surface drip irrigation obtained the greatest water use efficiency and should be recommended under Mediterranean conditions for potato production [9,40]. Rolbiecki et al. [41] reported a 55% increase in marketable yield of potato cultivar Courage compared to rainfed production in Poland. Slatni et al. [42] investigated the effect of alternate furrow irrigation, fixed furrow irrigation, and conventional furrow irrigation and found the average irrigation amounts were 65, 60, and 91 mm, and the water productivity values amounted to 8.0, 8.7, and 5.9 kg m⁻³ for the respective treatments with no yield reduction under the alternate furrow irrigation. Xie et al. [43] compared conventional furrow irrigation with the partial root-zone drying irrigation system at different watering levels and found that applying 50% of the supplementary water requirement did not affect fresh tuber yield and water use efficiency under both irrigation methods. Under arid and semiarid conditions and low soil water retention capacity, the adoption of plastic mulching and drought-tolerant potato cultivars help to achieve high tuber yield and improve water and fertilizer use efficiency [43].

Sarker et al. [44] compared alternate furrow irrigation, fixed furrow irrigation, and every furrow irrigation and found that potato tuber yield, tuber quality, and potato water productivity were affected by alternate furrow irrigation in a raised bed system while potato yield did not differ significantly between the alternate furrow irrigation and every furrow irrigation system. Overall, alternate furrow irrigation saved 35% of irrigation water and significantly improved irrigation water productivity by 50% compared to every furrow irrigation treatment. The alternate furrow irrigation could be an alternative to every or fixed furrow irrigation in South Asian countries with limited irrigation water availability [44]. Trout et al. [45] found that Russet Burbank produces better visual quality tuber and much lower incidence of sugar ends under sprinkler irrigation than under furrow irrigation due to less water stress, better nitrogen management, and lower soil temperature under sprinkler irrigation compared to furrow irrigation.

Table 1. Potato seasonal water use under different irrigation methods and rainfed conditions across different locations.

Locations	Seasonal Precipitation (mm)	Watering Regime	Irrigation Amount (mm)	Seasonal Water Use (mm)	Irrigation Method	Seasonal ETc (mm)	Potato Cultivar	Reference
Oregon				649	Sprinkler irrigation	300–655.1	Russet Burbank	Hane and Pumphrey [22]
India				350–650				Sood and Sing [23]
Lebanon			562.9–638.3		Drip irrigation	490–622	Agria	Karam et al. [25]
Turkey	142–512	Irrigated	88 to 302	244–780	Drip irrigation	166–473	Marfona	Onder et al. [9]
Saudi Arabia		Irrigated	783–1505	783–1505	Drip irrigation			El-Abedin et al. [26]
Italy	181–278	Irrigated	118.5–330	299–608	Drip irrigation	295–484	Spunta	Paredes et al. [27]
Italy	171–282	Rainfed				186–219	Spunta	Paredes et al. [27]
Italy		Irrigated		413.2 ± 15	Drip irrigation	322.2–447.9	Spunta	Katerji et al. [29]
Canada	350.6	Rainfed				331.5	Reba	Parent and Anctil [30]
Peru	Desert with 23 mm	Irrigated	102.3–222.5		Furrow		UNICA	Yactayo et al. [31]
New Zealand	294.6–421.6	Irrigated	189.4–196.4	491–550	Sprinkler irrigation	491–611	Agria, Moonlight,	Fandika et al. [32]
New Zealand		Rainfed		491–550			Moe Moe, Tutaekuri	Fandika et al. [32]
China	150.9–208.2	Rainfed		150.9–208.2		216.5 to 249.3	Kexin 1	Chen et al. [28]
Turkey	59.3–156.7	Rainfed		195.2		167.7–222.6		Kiziloglu et al. [33]
Turkey	59.3–156.8	Irrigated		445.2	Surface irrigation	up to 475.2	Granola	Kiziloglu et al. [33]
Iraq	7.4		300–447	307.4–455.4	Furrow & drip irrigation	375.1–511.4	Bowren	Ati et al. [34]
Portugal				-		150 to 550	Desirée	Ferreira and Carr [35]
Turkey	50–111	Irrigated	293–675	404–626	Furrow & drip irrigation	464–683		Erdem et al. [36]
Italy	170–196	Irrigated	25–191	195–382	Drip irrigation	155–448	Spunta	Ierna and Mauromicale [37]
Ontario, Oregon		Irrigated	368–588	368–589	Sprinkler irrigation	-	Russet	Shock et al. [38],
Serbia	222.7–231.2	Irrigated	175–278	39,717–509.2	Drip irrigation	449.2–522.1	Kennebec	Aksic et al. [39]
Serbia	222.7–231.3	Rainfed		222.7–231.3	-	288.1–294.4	Kennebec	Aksic et al. [39]

3.2. Impact of Irrigation Regime on Potato Growth and Yield

Potato plants have a shallow rooting system which makes them very sensitive to water stress, requiring proper water management to avoid putting potato plants under drought conditions [6,8,9,11,12]. For potato production sustainability, moisture should be kept above 50% of the total available water of the site soil [46]. Jensen et al. [47] reported that 30% was the water-saving limit compared to the field capacity. Camargo et al. [48] suggested that applying 80 to 100% of irrigation requirements helps to achieve high biomass accumulation. Potato growth, yield, and yield component are affected by irrigation regimes mostly tuber bulking and ripening which are the water stress-sensitive stages [49]. Foti et al. [50] reported no significant yield difference between 100 and 66% of maximum evapotranspiration irrigation regimes on potato tuber yield while they obtained the highest tuber yield with 133% maximum evapotranspiration water supply. In contrast, Karafyllidis et al. [51] obtained the highest potato yield under 65% of maximum evapotranspiration. Iqbal et al. [52] reported that the potato growing stage is the least sensitive to water stress. Deficit irrigation strategies aim to expose crops to a certain level of water stress during either a particular growth stage or during the crop growing season with a non-significant impact on crop yield [53]. Fresh potato yield and total dry matter accumulation increase with water supply [48,54–57]. Potato tuber number per plant and total yield increase with adequate irrigation water management before and during tuber initiation [58–60] and the proper irrigation management after tuber initiation increases the size of tubers [61–65]. During a two-year experiment in the Central Bekaa Valley of Lebanon, Karam et al. [25] found the full irrigation treatment to overcome deficit irrigation at tuber bulking and tuber ripening by 12 and 43%, in the first year and 11 and 39% in the second year, respectively. Similarly, Fabeiro et al. [66] reported potato yield reduction under deficit irrigation during potato growth, tuber bulking, and ripening stages while the larger tubers were obtained under the fully irrigated potato and the ripening stage deficit irrigation, and the smallest tubers were obtained under the applied deficit irrigation during the growth period with a high tuber number per plant. Deblonde and Ledent [14] reported a 17% reduction in potato tuber number of six cultivars affected by water stress at Nodebais, Belgium, with no impact on the yield due to compensation by average tuber dry weight. Brocic et al. [67] reported yield reduction of potato cultivar Liseta under 70% partial root-zone irrigation and silty-clay soil compared to the full irrigation. Karam et al. [25] found a 12% and 42% reduction in potato marketable yield when deficit irrigation was imposed at tuber bulking and tuber ripening, respectively, compared to the well-irrigated treatment. Yield loss under deficit is compensated by an increase in tuber dry matter [25,55]. Yuan et al. [68] reported that potato fresh tuber and marketable yield increased with increasing irrigation regimes. Miller and Martin [69] reported that daily irrigation improved total tuber yield, the number of tubers, and the specific gravity compared to four-day interval irrigation. Byrd et al. [70] showed the potential for reduced irrigation management for sustainable potato production in Florida. Camargo et al. [48] found 80% of irrigation requirements showed statistically similar yields to 100 and 120% of irrigation requirements in Aguas Nuevas, Spain.

Comparing deficit irrigation and partial root-zone drying with full irrigation, El-Abedin et al. [26] found that the deficit treatment and partial root-zone drying decreased potato fresh and dry tuber yield compared to the full irrigation with no difference between the treatments for the number of marketable size tubers while the number of oversized tubers was significantly lower under the partial root-zone treatments than under the full irrigation treatment. They indicated that the highest number of tubers per plant was obtained under full irrigation treatment and the deficit irrigation at 50% of the full irrigation treatment produced 51%, 72.8%, and 136.9% more tubers than the deficit irrigation at 70%, partial root-zone drying at 70% and partial root-zone drying at 50%, respectively. Karam et al. [25] reported that 50% of tuber yield was constituted with the large size potatoes (>200 g) under the full irrigation treatment while that proportion was 48% under the deficit irrigation at tuber bulking and 46% under deficit irrigation at tuber ripening. A larger number of small tubers was obtained when deficit irrigation was applied during the

tuber bulking stage compared to the tuber ripening state. Wang et al. [71] reported that potato tuber yield, largest tuber weight, commodity tuber weight, dry matter accumulation, and vitamin C content increased with the increase in the fertilizer application rate and the dripper discharge rate. Elhani et al. [72] also demonstrated that tuber yield penalty was similar under partial root-zone drying compared to deficit irrigation. These management approaches may be used by potato seed producers for increasing the number of potato seeds per plant.

3.3. Potato Water Production Function

Linear relationships were developed between potato yield and the seasonal evapotranspiration with different regression slopes and different intercepts under different environments [37,66,68]. These regression relationships were impacted by the management practices, potato cultivars, and fertilization. Cappaert et al. [60] indicated that the greatest effect of the irrigation management during the potato tuber ripening stage is shown by the magnitude of the coefficient of the applied irrigation amount during ripening (w_3) within the linear production function. Kiziloglu et al. [33] found a linear relationship between potato yield and crop evapotranspiration with an R^2 of 0.94 in Turkey. A similar relationship was reported by Islam et al. [73], Unlu et al. [74], Ayas and Korukçu [75], Cantore et al. [76], and Camargo et al., [48]. Unlu et al. [74] reported a difference in the regression slopes between the sprinkler and trickle irrigation systems with high water productivity under sprinkler irrigation than under trickle irrigation in Turkey. In contrast, Aksic et al. [39] reported a quadratic relation between potato yield and crop evapotranspiration in Serbia.

Linear production function was developed by Fabeiro et al. [66] where potato cultivar Agria tuber yield is a function of the amount of irrigation applied (w_i) during potato growth (w_1), tuber bulking (w_2), and ripening (w_3) stages in Spain [yield = $44.65 w_1 + 17.14 w_2 + 242.41 w_3$; $R^2 = 0.993$]. The same authors also reported quadratic relationship between tuber yield and the seasonal applied water (w) [yield = $38.067 - 0.0087 w + 0.000001639 w^2$; $R^2 = 0.742$]. Ross [77] found a cubic polynomial relationship between potato yield and the seasonal applied irrigation water amount. Badr et al. [78] found a linear relationship between potato tuber yield and the seasonal water supply with a quite high R^2 value of 0.973 and a regression slope of 92 kg/ha for unit mm of applied water. Yuan et al. [68] reported a quadratic relationship between potato yield per plant and the irrigation water supply (w) with R^2 of 0.98 [yield = $-0.0092 w^2 + 7.52 w - 409.47$]. Karam et al. [25] found a strong quadratic relationship between fresh potato tuber yield (Cultivar Agria) (kg/ha) and the seasonal applied irrigation amount w (mm) with R^2 value of 0.82 [yield = $-0.9277 w^2 + 1184.3 w - 314,999.9$; $R^2 = 0.82$].

Overall, potato yield has a strong linear relationship with crop seasonal evapotranspiration while it has a polynomial relationship with the seasonal applied irrigation amounts. However, these relationships may greatly vary in terms of the linear regression slopes, the intercepts, the constants within the polynomial, and the coefficient of determination as influenced by crop management practices, irrigation methods and scheduling, potato genotypes, soil types, climatic conditions, and other factors.

3.4. Potato Water Use Efficiency (WUE)

Potato has been reported to have a high water use efficiency (WUE) among the major food crops and which varied from 6 to 11.6 kg/ha/m³ [4]. However, potato WUE strongly depends on the genetic material, management practices, irrigation regime, fertilizer rate, and other environmental conditions. Modern potatoes have high WUE, but they are not as economically productive under the same volume of water as heritage potatoes [32]. Deficit irrigation strategies in crops are revealed to optimize crop WUE [79–84]. Onder et al. [9] reported potato irrigation water use efficiency (IWUE) that varied from 9.33 to 36.44 kg/ha/m³ under surface drip irrigation and from 9.05 to 30.12 kg/ha/m³ with the greatest IWUE obtained by treatment 33% of maximum evapotranspiration. The total water productivity varied from 6.17 to 14.01 kg/ha/m³ [9]. Yactayo et al. [31] reported an increase

in potato water use efficiency with an early partial root-zone drying, initiated 6 weeks after planting, with a watering level equivalent to 50% of full irrigation, with no yield reduction compared to fully irrigated potato in Peru. Potato economic water use efficiency, which is the reflection of marketable yield, varies with cultivars, irrigation regimes fertilization [32]. Ahmadi et al. [85,86] reported a significant decrease in potato IWUE under the partial root-zone drying (31–41%) compared to the full irrigation treatment. Fandika et al. [32] found potatoes WUE varying from 5.2 to 11.8 kg/ha/m³ under irrigation, from 9.0 to 12.9 kg/ha/m³ under rainfed production and was 8.3 kg/ha/m³ under 80 kg N/ha and 7.0 kg/ha/m³ under 240 kg N/ha in New Zealand. WUE decreased therefore with increasing irrigation regimes and increasing nitrogen applied rates. Paredes et al. [27] also found an increase in the IWUE under 50% deficit irrigation compared to the full irrigation treatment. They pointed to large IWUE differences between irrigation treatments as also shown by Trebejo and Midmore [87] and Ahmadi et al. [88] however, the differences were small between treatments when the seasonal precipitation, total water supply, and seasonal crop evapotranspiration were considered [27,42,89]. Chen et al. [28] indicated that straw strips mulch on furrows improved rainfed potato WUE by up to 74.8% and yield from 36.6 to 61.2% in Dingxi City, Gansu Province, China. El-Abedin et al. [26] found a reduction in potato irrigation water use efficiency (IWUE) by 33.8 and 36.1% under partial root-zone drying 70 and 70% compared to the full irrigation in 2014, respectively, while the reduction was 26.6 and 46.6% under the respective treatments in 2015. They also found that deficit irrigation at 70 and 50% of the full irrigation also decreased potato IWUE by 18.94 and 22.19%, respectively one year over two. However, the deficit irrigation a 70 and 50% of the full irrigation treatment showed higher IWUE (5.80 and 6.30 kg/ha/m³) than the partial root-zone drying technology at the same rates (4.41 and 3.21 kg/ha/m³). The improvement in IWUE under deficit irrigation compared to the partial root-zone drying was reported by Liu et al. [90]. Kriedmann and Goodwin [91] indicated that yield maintenance and IWUE improvement are the advantages of the partial root-zone drying technology over the regular deficit irrigation strategy. Partial root-zone drying has improved potato IWUE in the United Kingdom [92]. Under arid and semiarid climates, the duration of the wet/dry cycling in the partial root-zone drying decreases, and the crop is not exposed to extreme and severe water stress compared to the classic deficit irrigation [26,93]. Moreover, the partial root-zone drying practice should be started five to six weeks after tuber initiation [31,82,94]. In contrast, Shahnazari et al. [95], Ahmadi et al. [85] and Jovanovic et al. [96] reported higher potato IWUE under the partial root-zone drying than under deficit irrigation. Potato yield was similar under partial root-zone drying, deficit irrigation, and full irrigated potato while the partial root-zone drying and the deficit irrigation improved IWUE by 60% with 30% of the irrigation water saving in Denmark. Similarly, Liu et al. [97] found no potato yield improvement and IWUE under partial root-zone drying compared to the classic deficit irrigation. El-Abedin et al. [26] indicated that the contrasting results might have resulted from differences in the experiment set up, potato cultivars, climate, soil types, root distribution, and soil water balance.

3.5. Impact of Irrigation on Diseases in Potatoes

Potatoes are grown under different irrigation methods as surface irrigation, drip irrigation, and sprinkler irrigation. Irrigation management is critical for the management of fungal and bacterial diseases in potato crops such as hallow heart, late blight, early blight, while mold, bacteria stem rot, early drying, bacterial ring rot, etc. High and continuous humidity within potato crop canopy is favorable for pathogen germination and growth, reproduction, dispersal, and survival [98]. Irrigation can 'create a favorable environment for potato soil-borne diseases such as *Rhizoctonia* canker and black scurf (*Rhizoctonia solani*), common scab (*Streptomyces scabiei*), powdery scab (*Spongospora subterranea* f. sp. *Subterranean*), white mold (*Sclerotinia sclerotiorum*), silver scurf (*Helminthosporium solani*) pink rot (*Phytophthora erythroseptica*) and Verticillium wilt (*Verticillium dahlia*). Sprinkler irrigation, an overhead irrigation method creates high humidity on the potato leaves and within the

canopy, creating a micro-climate favorable to the development of potato foliage diseases such as early blight, late blight, bacterial stem rot, and white mold. It is therefore important to allow foliage to dry between irrigation and late afternoon and early evening irrigation events keep leaves wet during the night, which may increase the potential of occurrence of late blight, should be avoided [99]. While drip irrigation is usually assessed as water-saving technology, it has limited potential to create favorable conditions for potato foliar diseases. In contrast, recurrent mite infestations may increase mostly under subsurface drip-irrigated potato production. Menzies [100] reported that sprinkler irrigation increases the occurrence of fungal and bacterial foliar diseases. During the planting-sprouting stage, irrigation may increase soil moisture content while the potato seeds have enough moisture to support sprouting to emergence. Any irrigation event during that stage will decrease soil aeration to a level that is favorable to several pathogens, most notable bacterial soft rot or black leg (*Erwinia carotovora*), and stem and stolon canker (*Rhizoctonia solani*) development [101]. Rupp and Jacobsen [102] suggested avoiding over-irrigation to control aerial stem rot and early blight and recommended the use of less frequent irrigation with longer duration and early day irrigation to allow for drying to occur later in the day, and no irrigation should occur in cool cloudy conditions. Alternaria brown spot known as brown leaf spot caused by the fungus *Alternaria alternata*, is more severe with overhead irrigation. The soft bacterium is spread by irrigation, splashing water, or insects. In contrast, the potato common scab (*Streptomyces scabies*) on the potato cultivar Russet Burbank was controlled by maintaining soil moisture content above 90% of the total soil available water during six to nine weeks. Olanya et al. [103] have compared the microclimate created by sprinkler irrigation, surface drip irrigation, and subsurface drip irrigation on Russet Burbank potato in Maine (USA) and found that the irrigation application method did not consistently impact microclimatic parameters associated with late blight development. Larkin et al. [104] found an increase in potato back surf caused by *Rhizoctonia solani* and common scab caused by *Streptomyces scabiei* under irrigated treatment compared to rainfed treatment. However, previous research showed that irrigation during the six weeks following tuber initiation tends to reduce common scab in potatoes [105,106]. Davis and Everson [107] reported more severe Verticillium wilt in potato under furrow irrigation than under sprinkler irrigation. Irrigation can also be used in combination with pesticides as chemigation to control foliage pests in potatoes if the product is allowed chemigation.

Diverse diseases in potatoes are transmitted by mostly phytophagous pests feeding on the vascular system of the potato plant. For example, the potato psyllid (*Bactericera cockerelli*) is one of the most important pests in potatoes (*Solanum tuberosum* L.) due to its feeding behavior and the transmission of a bacterium (*Candidatus Liberibacter solanacearum*) that causes zebra chip disease, altering the quality of the potato tuber and the fried potato chips or French fries [108–112]. Aphids especially the green peach aphid (*Myzus persicae*) and Potato aphid (*Macrosiphum euphorbiae*) transmit potato leafroll virus which reduces marketable potato yield causing phloem net necrosis, a brown discoloration inside the potato that reduces quality and other viruses cucumber mosaic and alfalfa mosaic (calico) inducing a wide variety of foliar and tuber symptoms, leading to severe yield reduction and loss of tuber quality [113,114]. *Myzus persicae*, *Rhopalosiphum padi*, *Aphis fabae*, and others are well known to transmit Potato Virus Y (PVY) which impacts potato yield and quality [115,116]. When aphids' infestation occurs, irrigation should be stopped to allow slow dehydration of potato foliage and desiccation which triggers wind formation in aphids and stimulus for flights [117]. However, this should be the last option as reducing and stopping irrigation may be detrimental to potato tuber yield and quality.

Spider mites are basically abundant under severe drought and hot conditions and they colonize stressed plants under poorly managed irrigation scheduling [118]. Mites *Tetranychus urticae* and *Polyphagotarsonemus latus* (Arachnida: Trombidiformis, Tarsonemidae) are polyphagous and can build high populations in a very short time during the hot dry season when the air temperature is above 30 °C. The fungal potato pathogen *Streptomyces* spp is associated with mite and causes scab in potatoes [119]. Besides the chemical control,

sprinkler irrigation helps to limit mite damage by increasing the humidity on plant leaves (>60%).

The potato tuberworm, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) is a major pest in potatoes that feed on potato leaves with less significant yield lost and tuber infestation reduces the marketable yield. The larvae mine leaves, stems, petioles, and excavate tunnels through potato tubers, which is considered the typical damage. Insecticide application is the main method used to control the pest however, cultural practices such as irrigation management are used for sustainable management. Meisner et al. [120] reported that the female moths prefer dry soil for oviposition and the larvae survival increases with low soil moisture content [121]. It is therefore important to keep soil moisture high through sprinkler irrigation and avoid cracks in the soil mostly during the late-season stage with vine senescence, and after vine kill. Rondon et al. [122] and Clough et al. [123] suggested that applying 2.5 mm/day through a center pivot irrigation system from vine kill to harvest decreased *P. operculella* tuber damage and did not increase fungal or bacterial diseases. Table 2 summarizes some irrigation management favoring diseases in potatoes and other water management to reduce the impact of the diseases.

Table 2. Irrigation management favoring diseases in potatoes and irrigation practices to reduce the impact of the diseases.

Disease	Pathogen	Favorable Conditions	Irrigation Practices to Reduce the Diseases	Reference
fungal and bacterial folial diseases.	Fungi and bacteria	High-frequency sprinkler irrigation	Less frequent high rate irrigation and early day irrigation	[100]
bacterial soft rot or black leg	<i>Erwinia carotovora</i>	Irrigation during Planting	No irrigation during	[101]
stem and stolon canker	<i>Rhizoctonia solani</i>	-sprouting stage	Planting-sprouting stage	[101]
aerial stem rot	Phytophthora nicotianae, Pectobacterium carotovorum, Pectobacterium atrosepticum, Dickeya dianthicola	Sprinkler over-irrigation, dense canopies, excessive nitrogen fertilization	Avoid over-irrigation, use less frequent irrigation, with longer durations. Early day irrigation	[102]
Potato common scab	Streptomyces scabies	over-irrigation	Soil moisture content > 90% total soil available water during 6 to 9 weeks	[102]
Ring rot	Clavibacter michiganensis	Drought and heat stress	Keep surfaces wet	[102]
Alternaria brown spot	Alternaria alternata	Overhead irrigation	Avoid irrigation in cool, cloudy conditions	[102]
Early blight	Alternaria solani	Overirrigation	Avoid over-irrigation, allow leave to fully dry	[102]
Late blight	Phytophthora infestans	Overhead irrigation during	Monitor irrigation so that leaves dry during the day, avoid excessive fertilization	[102,103]
Potato back	Rhizoctonia solani	Irrigated cropping	regulated deficit irrigation	[104]
Common scab	Streptomyces scabiei	Irrigated cropping	Safe deficit irrigation, irrigation during the 6 weeks following tuber initiation	[104–106]
Verticillium wilt	Verticillium dahliae	Furrow irrigation	Sprinkler irrigation, irrigation management prior to tuber initiation)	[107]
Zebra chip	Candidatus Liberibacter solanacearum	Bactericera cockerelli	Stop irrigation for leaf dehydration and desiccation	[108–112]

Table 2. Cont.

Disease	Pathogen	Favorable Conditions	Irrigation Practices to Reduce the Diseases	Reference
PVY	Potato virus Y	Myzus persicae, Rhopalosiphum padi, Aphis fabae	Stop irrigation to allow slow dehydration of potato foliage and desiccation	[113–117]
Tetranychus urticae, Polyphagotarsonemus latus		Drought and heat stress (temperature > 30 °C)	Sprinkler irrigation helps to limit mite damage	[118]
scab in potatoes associated with mites	Streptomyces spp	Drought and heat stress (temperature > 30 °C)	Sprinkler irrigation helps to limit mite damage	[119]

3.6. Impact of Irrigation Regime on Potato Specific Gravity and Chemical Content of the Tubers

Specific gravity is one of the characteristics of potato tuber, and determinant for harvest quality. It is a measurement of the starch or solids content relative to the water content in a potato. High dry matter content is a synonym of low water content and vice versa. It is used by the potato industry for harvest storability, fry quality appreciation, and baking characteristics. Miller and Martin [69] reported that daily irrigation increased potato specific gravity compared to four-day interval irrigation. Yuan et al. [68] indicated that specific gravity tended to decrease with increasing irrigation depth. In contrast, water stress in potato improves the chip quality due to the higher content of tuber dry matter [124]. However, Hang and Miller [125] and Shock et al. [65] indicated that deficit irrigation trended to decrease tuber specific gravity. Similar findings were reported by Waddell et al. [126] who found that the specific gravity of tubers from the relatively stressed treatments was significantly lower than the specific gravity of tubers from the well-irrigated treatment under sprinkler irrigation. Poter et al. [127] found that tuber-specific gravity decreased with increasing irrigation rates while Drewitt [128] reported an increase in specific gravity with an increase in irrigation frequency. Early appropriate stages irrigation increases tuber dry matter and continuous or late-season irrigation can reduce potato dry matter content [129]. Peterson and Weigle [130] indicated that tuber specific gravity increased under mist irrigation conditions. Reduction in tuber-specific gravity associated with late-season irrigation was reported by Silva et al. [131]. After wine kill, tuber specific gravity decreases with desiccation [132,133].

Studies have revealed that irrigation management can affect the quality of the production and the chemical composition of tubers during the storage period which is particularly critical for the chip potato industry. Potato dry weight is constituted mainly by starch and small quantities of sugars, fiber, protein, and ash. Potato tuber content in sucrose, glucose, and fructose are important factors affecting the color of the processed products such as French fries and chips in potatoes [134,135]. Jovanovic et al. [96] pointed that the partial root-zone drying irrigation management results in a slight reduction in soluble sugar content and an increase in starch, nitrogen, and antioxidant contents of potato tubers. Sarker et al. [44] found potato soluble sugar also varied significantly between the alternate furrow irrigation and every furrow. Eldredge et al. [64] found an increase in potato tuber sugar content promoted by drought stress. Comparing partial root-zone drying to deficit irrigation, Elhani et al. [72] reported a decrease in potato tuber sugar and protein content with the increase in water stress with higher values in partial root-zone drying than in deficit irrigation treatment as shown by Battilani et al. [136]. Adversely, the polyphenols and antioxidants amount increased in potato tubers with increasing water stress on potato plants. There was also higher metabolite content in potato tubers under partial root-zone drying than under deficit irrigation with less decrease in glucose and fructose concentrations and with double the amount of mannitol [72]. In contrast, Elhani et al. [72] found that tuber content in glucose and fructose gradually decreased with decreasing seasonal water supply and similar findings were reported by Wegener et al. [137] who reported a decrease in total sugars, glucose, and fructose with increasing water stress in potatoes.

The inconsistency of the effect of the drought stress on the sugar content of the tubers is genotype/cultivar dependent [138,139].

Protein content in the potato tubers is an important nutritional characteristic [140] and is usually impacted by the irrigation regime and plant nitrogen fertilizer uptake and remobilization. Plant nitrogen content decreases under drought conditions [141]. However, Elhani et al. [72] reported an increase in potato tuber protein content under the partial root-zone drying treatment, and which might have been possible due to the increase in nitrogen mineralization with the increase of the frequency of the wet/dry cycles [47,142] or the promotion of nitrogen uptake [143].

Polyphenols are the other main constituents of potatoes which are influenced by crop water management. Hamouz et al. [144] found that the polyphenols contents were increased under drought stress compared to the well-irrigated treatment under extreme temperature. Elhani et al. [72] reported an increase in tuber polyphenols content with an increase in water stress. This phenomenon is due to the alteration of sucrose flux induced by water stress which changes the expression of the responsible polyphenol synthesis genes [138]. Andre et al. [138] indicated that there is a correlation between diverse polyphenolic profiles and the variations in gene expression profiles and the drought-induced variations of the gene expression were highly genotype-specific. Some potato tuber quality indexes as impacted by management practices are summarized in Table 3 with the best water management practice to reduce the induced unfavorable quality.

Table 3. Potato tuber quality as impacted by management practices.

Quality Index	Trend	Cause	Best Practices	Reference
Specific gravity	Decrease	Four-day irrigation scheduling	Daily irrigation	Miller and Martin [69]
Specific gravity	Decrease	High irrigation rate	Meet crop ETc	Yuan et al. [68]
Specific gravity			Meet crop ETc	[124]
Specific gravity	Decrease	Deficit irrigation	Meet crop ETc	Hang and Miller [125]
Specific gravity	Decrease	Deficit irrigation	Meet crop ETc	Shock et al. [65]
Specific gravity	Decrease	Drought	Meet crop ETc	Waddell et al. [126]
Specific gravity	Decrease	Increasing irrigation	Meet crop ET	Poter et al. [127]
Specific gravity	Increase	High irrig. frequency		Drewitt [128]
Specific gravity	Decrease	Continuous late irrigation	Reduce irrigation frequency late season	[129,131]
Specific gravity	Increase	Mist irrigation		Peterson and Weigle [130]
Specific gravity	Decrease	Desiccation after wine kill	Light irrigation after Wine kill	[132,133]
Sugar content	Reduce	PRZDI	Meet crop ETc	Jovanovic et al. [96]
Sugar content	Reduce	Alternate Furrow	Every furrow	Sarker et al. [44]
Sugar content	Increase	Drought		Eldredge et al. [64]
Sugar content	Decrease	Drought	Meet crop ETc	Elhani et al. [72]
Sugar content	Decrease	Deficit irrigation	PRZDI	Battilani et al. [136]
Metabolite Mannitol content	Increase	Deficit irrigation	Meet crop ETc	Elhani et al. [72]
Sugar contents	Decrease	Water stress	Meet crop ETc	[72,137]
Sugar C content	Inconsistent	genotype/cultivar dependent		[138,139]
Protein content	Decrease	Drought	Meet crop ETc	[141].
Protein content	Increase	PRZDI		[47,72,142,143]
Polyphenols	Increase	Drought	Meet crop ETc	[72,144,145]
Sugar end/called dark ends	Increase	Heat, drought	Meet crop ETc	[59,146–154]
Sucrose	Increase	Water stress	Meet crop ETc	Thompson et al. [150]
phenyl-propanoids	Increase	Drought	Meet crop ETc	[155–158]
Sugar end/called dark ends	Increase	Excessive nitrogen fertilizer	Meet crop need	[155,156]
Sugar end/called dark ends	Increase	Inadequate phosphorus fertilizer	Meet crop need	[157]
Stem end	Significant	Water stress	Meet crop ETc	Eldredge et al. [64]

In summary, the impact of irrigation water management on the potato chemical content might be genotype-dependent, however, more collaborative research involving potato breeders, geneticists, crop physiologists, and agronomists should be conducted

under severe and medium drought stress and under different climates conditions to determine the factors affecting potato tubers chemical contents and the influencing factors.

3.7. Impact of Irrigation Regime on the Potato Fries and Chips

Sugar end, also called dark ends, jelly ends, translucent ends and glassy ends [145–149], are the results of physiological disorder in potato under stress conditions with an increase in sugar content in the basal end of the tuber and low starch content. At fry, the processed product presents one dark end and is not appreciated by the consumers. Sugar end can be detrimental for potato growers. Thompson et al. [150] reported that stressed plants accumulate large amounts of sucrose in the basal tissues of the tuber immediately following stress and continue producing adequate amounts of assimilation to support tuber growth. Heat stress and water deficit are the factors that induce changes in the activities of certain key carbohydrate metabolizing enzymes shifting the tuber from a starch synthesizing function to one of starch mobilization [59,146,148,150–154]. Under drought conditions, reactive oxygen species can arise and lead to oxidative damage within the cells with an increase in the production of metabolites such as phenyl-propanoids with antioxidant properties, able to scavenge reactive oxygen species [155–158]. Late embryogenesis of abundant proteins and heat proteins is the protection mechanism in drought stressed potato [72,139,159–165] with an accumulation of osmolytes derived from amino acids or carbohydrates [164,166–168]. These amino acids cause a bitter and astringent taste called egumi-taste in cooked or processed potato tubers [169]. Other studies have shown that excessive nitrogen fertilizer rates [170,171] and inadequate phosphorus fertilizer [172] are other factors of the sugar end in potatoes. Eldredge et al. [64] found a significant darkening in the average stem-end fry color light reflectance of water-stressed Russet Burbank tubers at harvest and during the post-harvest period. Water deficits in potatoes throughout the growing season decreased photosynthesis and assimilate remobilization [173] and consequently fry potato presents pronounced sugar end while it was moderated when plants are subjected to a short duration of water stress [65].

3.8. Best Irrigation Management in Potatoes

From the aforementioned research results, water management in potato appears not straightforward. Irrigation management in potatoes like other crops should follow principles of plant-water relationships, irrigation scheduling, monitoring soil moisture across potato root zone throughout the growing season, relationship irrigation and potato growth stages, and considering irrigation and common scab and other characteristics of the product for the target market. Best water management practices must take into account environmental sustainability and economic profitability. For accuracy of irrigation matching crop actual evapotranspiration, potato growers need to learn at least one way to measure or estimate crop evapotranspiration, follow trends in soil moisture content and or soil water matric potential, and keep track of soil water storage and crop evapotranspiration [174]. The first option is to meet crop water requirement which depends on crop growth stages, crop environment, and other management practices. The guidelines proposed by Allen et al. [175] are a great tool for estimating crop evapotranspiration using local weather data and the adjusted proposed crop coefficients to potato height [27,176–178]. Potato is considered to be extremely sensitive to water stress during the tuber initiation and tuber bulking stages and any water deficit during these stages will affect crop yield and quality and the net economic return of the production system. Different available soil moisture sensors could be used for real-time soil storage management that helps to avoid water stress on the potato plant anytime the triggering point or the lower soil storage threshold is reached. Potato growers should consider 60 cm as the maximum potato plant root zone in the irrigation depth estimation and assure uniform water distribution. Under limited water availability, deficit irrigation is a great option for increasing potato water use efficiency however, the threshold should be set according to the soil type, water availability, and economic profit targets. In arid and semiarid conditions with hot air temperatures, it is recommended

to use an overhead irrigation system to limit mite infestation. Crop producers should refer to extension agents and or crop consultants or university researchers with any doubt about any uncommon phenomenon observed on the plants in their field for advice and problem-solving.

4. Conclusions

This review explored the effects of irrigation management on potato yield and quality, production function, diseases, and pests in potatoes. While targeting one objective can lead to other problems, potato growers should be aware of the contrasting results. However, the best irrigation management practices should be adopted to optimize the production system as suggested by Shock et al. [154]. Potato is a shallow-rooted crop and very sensitive to water stress. Basically, irrigation depth should match for evapotranspiration and any over-irrigation may promote the occurrence of diseases while water stress results in tremendous yield reduction and alters the profitability of the production system. To cope with climate change and production sustainability, smart and precision irrigation is recommended. Different decision tools are available to assist potato growers to achieve profitable and sustainable potato production. However, multidisciplinary studies including but not limited to agronomists, crop physiologists, irrigation engineers, potato breeders, entomologists, environmental engineers and pathologists, and economists may be conducted for an integrated approach to improve potato productivity and system sustainability under different climatic conditions.

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