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Article

Low Hanging Fruit' Practices for Improving Water Productivity of Rainfed Potatoes Under Integration of Cultivar Selection, Mulch Application, and Agroecological Zones in Sub-Tropical, Semi-Arid Regions

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Abstract: Unevenly distributed rainfall leads to reduced potato water productivity (WP) under rainfed production. Understanding practices that can increase WP is vital. Objectives were to (i) understand seasonal variables that influence WP under rainfed conditions and (ii) the effect of the integration of cultivar, locality, mulch on potato WP. The study was under two agroecological zones Appelsbosch (Mbalenhle locality), and Swayimane (Stezi, and Mbhava locality), under smallholder. A split plot, in a randomized complete block design experiment, consists of mulching (mulch and not mulch), and selected cultivars. Soil water content (SWC), yield, and climatic conditions were collected, water use (ET) and WP were calculated. Rainfall, ET, and SWC had a significant influence on seasonal WP. Cultivar x mulch x locality had an insignificant effect on WP, however, locality x cultivars significantly altered potato WP. Localities that had lower vapor pressure deficit (VPD), low relative humidity, and sandy soil had higher potato WP of 14.53 kg m^{-3}. The findings suggest that localities that have less atmospheric dryness and cultivars that show stability of yield across seasons can be an easy-to-apply practice for increasing potato WP under a resource-limited environment. Mulch is important when the distribution of intra-annual rainfall does not match crop water requirements.

Keywords: evapotranspiration; soil water content; atmospheric dryness; rainfall variability; yield

1. Introduction

Water productivity (WP) is the ratio of yields or biomass produced per unit of actual water used [1]. Potato (*Solanum tuberosum*) WP in the sub-Saharan African (SSA) region has been reported particularly in Ethiopia ranging from 3.56 to 8.70 kg m^{-3} [2], meanwhile in other regions such as Asia (Pakistan) ranged from 14.60 to 17.28 kg m^{-3} [3]. The low potato average yield of 6 to 10 t ha^{-1} of SSA [4] is attributed to low WP, exacerbated by high rainfall variability often accompanied by flash floods and intermittent dry spells, which cause water losses and crop water stress during the growing season leading to inefficient water use and decreases in yield [5]. Hence, SSA farming under rainfed is at risk due to climatic variability considering the high dependence on rainfall, also rainfall does not match crop water needs according to each growth stage, often creating a mismatch between the required potato water distribution and occurring rainfall [6]. Potatoes require the least amounts of

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water from planting to crop establishment (Kc = 0.4 – 0.5) and later towards crop maturity and harvest (Kc = 0.7 – 0.75) [7]. Water requirements gradually increase (Kc = 0.7 – 0.8) during the crop development phase due to vegetative growth and initiation of tuber development, with peak water requirements at the mid-season phase (Kc = 1.05 – 1.2) when peak photosynthesis and tuber bulking occurs [7]. Resource-constrained SA potato producers usually lack irrigation inputs, making potato production under smallholder settings highly reliant on rainfall and exposed to rainfall-related production risks especially when rainfall is a limiting factor [8].

Improving potato WP under rainfed growing conditions is linked to management practices related to changes in crop, soil, and water management. These practices include retaining and storing water during flash flood events, to ensure sufficient water during dry spells. Covering the soil with mulch to conserve soil moisture, increasing infiltration during heavy rain reducing soil evaporation, and restraining runoff [9]. This practice increases in simultaneous increases in crop and water productivity and has been observed to increase WP [10–14] in other settings, however, there is very low use of mulch in SSA by smallholder farmers, particularly in South Africa. Biswal et al. [14] reported that straw mulching significantly increased water productivity (30–39%). Another tool to improve WP is selecting agroecological zones that offer moderate temperatures, adequate rainfall, and fewer extreme events that are accompanied by high atmospheric dryness amplifying dry spell severity and soil moisture deficit during potato production, thereby negatively affecting plant water fluxes and crop yields [15].

Approximately 96% of smallholder farmers use uncertified seed, either potato retained from previous harvest (farmer-saved seed), sourced from neighbors, or purchased from local markets [16]. Uncertified poor-quality seeds from the informal sector, are generally less efficient in converting water into biomass and ultimately into yield. This results in higher usage per unit of yield produced, reducing overall water productivity. To increase the yield of potatoes for each unit of water transpired, the adoption of certified seed from improved cultivars is key to improving WP. Breeders have developed a range of cultivars that match growth cycles with the expected water supply or with the absence of crop hazards, which are tolerant to water stresses such as dry spells [17]. Selecting short to medium-duration cultivars increases WP by escaping late-season water stresses that adversely affect potato growth and development. Meanwhile, late-maturing cultivars can utilize the late-season rainfall. Farmers have a wide range of options in selecting cultivars that are customized to fit local climatic, as well as selecting agroecological that have certain soil types or hydrological properties that can be noted to help a farmer improve WP.

The application of mulch and cultivar selection to improve potato WP in different agroecological zones has been reported by a handful of studies [18, 19, 20], [11]. Despite the solution being put forward such that when using practices solely tends to give small investment returns, for instance, mulch alone does not always guarantee increases because it is scenario-specific (e.g weed control, soil improvement, plant health, moisture retention, etc.) each scenario may require different types of mulch. Cultivar selection alone does not always work out well, due to climate variability, and soils. The sustainable strategy is to combine these practices, such that if one fails one works. This integration of factors has not been studied, especially in the smallholder setting that has low yield translating to low WP. Hence integration approach responds to produce “more crops per drop” such as increasesing output per little water used, recucing losses of water through evaporation and other unproductive process, lastly improve efficiently use of rainfall. Therefore, the specific objectives were to determine (i) understand the seasonal variables influence on seasonal potato water productivity under dryland conditions and (ii) the impact of integration of cultivar selection, application of mulch and locality on potato WP. Further more this study contribute to the selection of cultivars can can improve potato WP and practices that can be used to achieve high yields and WP of potatoes under smallholder settings. In South Africa, there is limited knowledge of the practices that are used by smallholder farmers and quantities of potato yield are very difficult to obtain in this setting, hence this study will cover that research gap.

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2. Materials and Methods

2.1. Potato Cultivars Selection

The potato cultivars (Table 1) (Mondial, Sababa, Panamera, and Electra) were sourced from Wesgrow (Pty) Ltd. Cultivars that were selected varied in seasonal length and drought tolerance.

Table 1. Cultivars characteristics.

Cultivar	Drought tolerance	Length of the growing season	Maturation period (days)
Electra[1]	Good	Medium late	110-150
Mondial[1]	Good	Medium late	110-150
Panamera[1]	Susceptible	Late	110-150
Sababa[2]	Good	Medium	90-110

Source: [1][21]; [2][22].

2.2. Field Description and Climate Data

The field trials were conducted in two different agroecological zones in Swayimane (Stezi and Mbhava) and Appelsbosch (Mbalenhle) in KwaZulu-Natal, South Africa. Swayimane and Appelsbosch represented macro-climatically different agroecological. Appelsbosch has cooler, highly humid, drier climates with lower clay content soils that are sandy loam in texture. On the other hand, Swayimane has warmer, moderately humid, wetter climates with high clay content soils that are sandy clay in texture. Swayimane was further divided into two different micro-climatic locations even though they are under the same bioresource groups (BRG), which are Stezi and Mbhava. Stezi is a high-lying (hilltop), warmer, north-facing (sun-facing) slope (Table 2). Ironically, Stezi means high heights which match the description of a high-lying area in this instance. Stezi was expected to have high atmospheric dryness due to its warmer and drier atmosphere compared to Mbhava. Mbhava is a low-lying (valley), cooler, south-facing slope (Table 2). Before initiating planting, automatic weather stations (Davis 6152 Wireless Vantage Pro 2) were installed on the experimental sites, and data such as temperature, rainfall, reference evapotranspiration, and relative humidity were collected. Furthermore, the characterization of soil was done to determine soil forms [23] for each experiment before planting. Afterward SPAW model [24] was used to get the soil hydraulic and physical properties are represented in Table 3.

Table 2. Bioresource group classification and climate of the Appelsbosch and Swayimane planting sites.

Macro-climate (agroecology)	**Appelsbosch**	**Swayimane**	
Micro-climate (locality)	Mbalenhle	Stezi	Mbhava
Coordinates	29°22'33.88''S 30°52'4.84''E	29°31'51.10''S 30°35'24.42''E	29°33'54.98''S 30°39'44.64''E
Elevation (m.a.s.l)	1003	874	750
Average air temperatures (°C) [1,2]	17.1	18.7	18.7
Humidity levels [1,2]	High	Moderate	Moderate
Annual mean and range of rainfall (mm) [1,2]	650 (500 – 800) [1]	800 (600 – 1100) [2]	800 (600 – 1100) [2]
Aspect	North facing slope	North facing slope	South facing slope
Bio-resource group (BRU) [3,4]	Warm moist grass veld	Subtropical coastal	Subtropical coastal

[1][25], [2][26]), [3][27], [4][28].

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Table 3. Localities soil properties description.

Locality	Soil depth	Soil form	Textural class	Clay content	[1]PWP	[2]FC	[3]SAT
	(m)				%		
Mbalenhle	>1	Inanda (Umbrisols)	Sandy loam	20.7	22.1	33.7	43.7
Mbhava	>1	Hutton (Ferralsols)	Clay	50.4	24.3	36.5	45.3
Stezi	>1	Inanda (Umbrisols)	Sandy clay loam	26.6	23.1	39.1	46.7

[1] Permanent wilting point, [2] field capacity, [3] saturation.

2.3. *Experimental Design and Field Management*

Soil samples were collected at each site for soil fertility analysis, analysis was done at Cedara Soil Analytical Services [29] and fertilizer (KCl and 2:3:4 (30)) was applied using on the soil fertility analysis. The field trial was in the 2022/23 and 2023/24 planting seasons (August to January) in the above-mentioned localities (micro-climates). A split-plot layout was used in a randomized complete block design. Grass hay mulch (not mulch and mulch), locality (Mbhava, Stezi, and Mbalenhle), and cultivars (Panamera, Electra, Sababa and Mondial) were tested. The pre-sprouted seeds were manually planted on a 13.5 m^2 plot with a spacing of 0.3 m x 0.9 m. Upon crop establishment stage 1.9 kg m^{-2} mulch was applied evenly. Dithane M45 (3 kg ha^{-1}), Ridomil (2.5 L ha^{-1}) and Bravo (1 L ha^{-1}), Bravo (1 L. ha^{-1}) fungicides were used weekly to control blight diseases upon disease incident, insect was controlled as well using Cypermethrin and Decis at a rate of 0.150 L. ha^{-1} [30]. Weed was manually removed during the growing season, and round-up (5 L. ha^{-1}) was only used before plowing the soil [30].

2.4. *Collection of Field-Measured Variables*

2.4.1. Growth and Phenological Parameters

The canopy cover was collected using the Canopeo v2.0 application, the captured high-resolution image, the application evaluated pixels of the image based on the red-to-green (R/G), and blue-to-green (B/G) color ratios [31]. The result output image is in black and white, the green area is represented by white, and black is the non-green area. Thereby maximum canopy cover was the highest percentage of canopy cover, meanwhile duration of maximum canopy cover was the number of days between maximum canopy decline and days when maximum canopy cover was reached. Phenological data included time taken to reach physiological maturity and was measured when 50% of plants per plot showed some signs of yellowish leaves (senescence). At harvest, yield was measured on the experimental plot, two-center rows.

2.4.2. Crop Water Use

Weekly soil water content (SWC) was measured using a Diviner 2000 (Sentek Environmental Technologies, Stepney, Australia) through PVC access tubes that were installed on the day of planting at the center of the plot, and the first reading was taken on the same day. The reading was done on different depth intervals of 10, 20, 30, 30, 40, 60, 70, 80, 90, and 100 cm as the percentage of soil water content. Furthermore, measured SWC was used to calculate soil water balance from planting to physiological maturity as shown below.

$$ET = P - \Delta SWC \quad (1)$$

where ET is actual crop water use, P is rainfall and SWC is the change in soil water content (soil water content at harvest - soil water content at planting). The study was conducted under rainfed conditions hence irrigation was ignored, and runoff, capillary rise, and drainage were negligible. The cultivars reached physiological maturity on different days, hence rainfall used to calculate ET was based on days to reach maturity. Thereby water productivity (WP) was calculated using the following equation:

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$$\text{WP= Yield/ actual water use} \quad (2)$$

2.4.3. Vapor Pressure Deficit

The vapor pressure deficit was calculated with the following equations (3) to (6) [32]:

$$e^{\circ}(T) = 0.6108 \exp\left[\frac{17.27\,T}{T+273.3}\right] \quad (3)$$

$$e_s = \frac{e^{\circ}(T_{max}) + e^{\circ}(T_{min})}{2} \quad (4)$$

$$e_a = \frac{e^{\circ}(T_{min})\frac{RH_{max}}{100} + e^{\circ}(T_{max})\frac{RH_{min}}{100}}{2} \quad (5)$$

$$VPD = e_s - e_a \quad (6)$$

where e° (T) is the saturation vapor pressure at air temperature T (°C), Tmax is the daily maximum temperature, Tmin is the minimum temperature, RHmax is the maximum relative humidity, RHmin is the minimum relative humidity, es is saturated vapor pressure, ea is actual vapor pressure and VPD is vapor pressure deficit.

2.4.4. Statistic Analysis

GenStat software (GenStat®, 23rd edition [64 Bit] VSN International, UK) was used to analyze data. Tukey was used for the mean separation test at $p<0.05$. The association of seasonal variables was correlated using GenStat.

3. Results and Discussion

3.1. Potato Cultivars' Response to Weather Data

The optimum temperatures for potato growth are 7°C -20°C [33], the obtained minimum temperature ranged from 4.6 to 6.9°C, across localities with no cold stresses. Temperatures were low at the beginning of the season but became warmer as the season progressed with no observation of heat stress (Figure 1). Both seasons received a high amount of seasonal rainfall ranging from 540.3 to 774 mm, however, both seasons received rainfall was unevenly distributed, and did not match to crop coefficient (Kc) water requirement, such that a huge amount of rainfall received in the late season stage (Figure 1) when it was not needed in abundance. However, the 2022/23 season showed less erratic in a way that rainfall nearly matched crop water demand. Hence the rainfed setting is at risk and vulnerable to this climatic variability. The localities showed similar rainfall patterns, however, Mbalenhle received more rainfall (235 mm) for the 2023/24 season in the development stage compared to other localities which is the stage where tuber starts to form and adequate moisture is important. In both growing seasons, reference evapotranspiration (ETo) (55.6 to 99.1 mm) was higher than rainfall at the initial stage, except for Stezi in 2022/23, the high atmospheric demand simply translated into water deficit in the soil, exposing potato plant intermittent drought [15]. The observed climatic data further emphasize that sufficient seasonal rainfall is so not important compared to the even distribution of rainfall that will proportionate with Kc. Hence, farmers can shift planting dates to make use of huge amounts of rainfall received in the late season. The low seasonal average relative humidity (61.4% and 66.4%) and high vapor pressure deficit (1.08 kPa and 1.14 kPa) observed in Mbhava for both seasons (Table 4) led to higher atmospheric dryness hence the daily average reference evapotranspiration (ETo) 4.06 and 3.94 mm day^{-1} (Figure 1) therefore this locality had drier atmosphere for potato growth which might affect crop transpiration. Meanwhile, Stezi and Mbalenhle were humid with an average daily VPD of 0.82 to 0.83 kPa and 0.74 to 0.78 kPa (Table 4). The high relative humidity for Stezi and Mbalenhle led to less atmospheric dryness hence the daily average ETo was 3.11 and 3.04 mm day^{-1}for 2022/23 and 3.29 and 2.91 mm day^{-1} for the 2023/24 season for Stezi and Mbalenhle, respectively.

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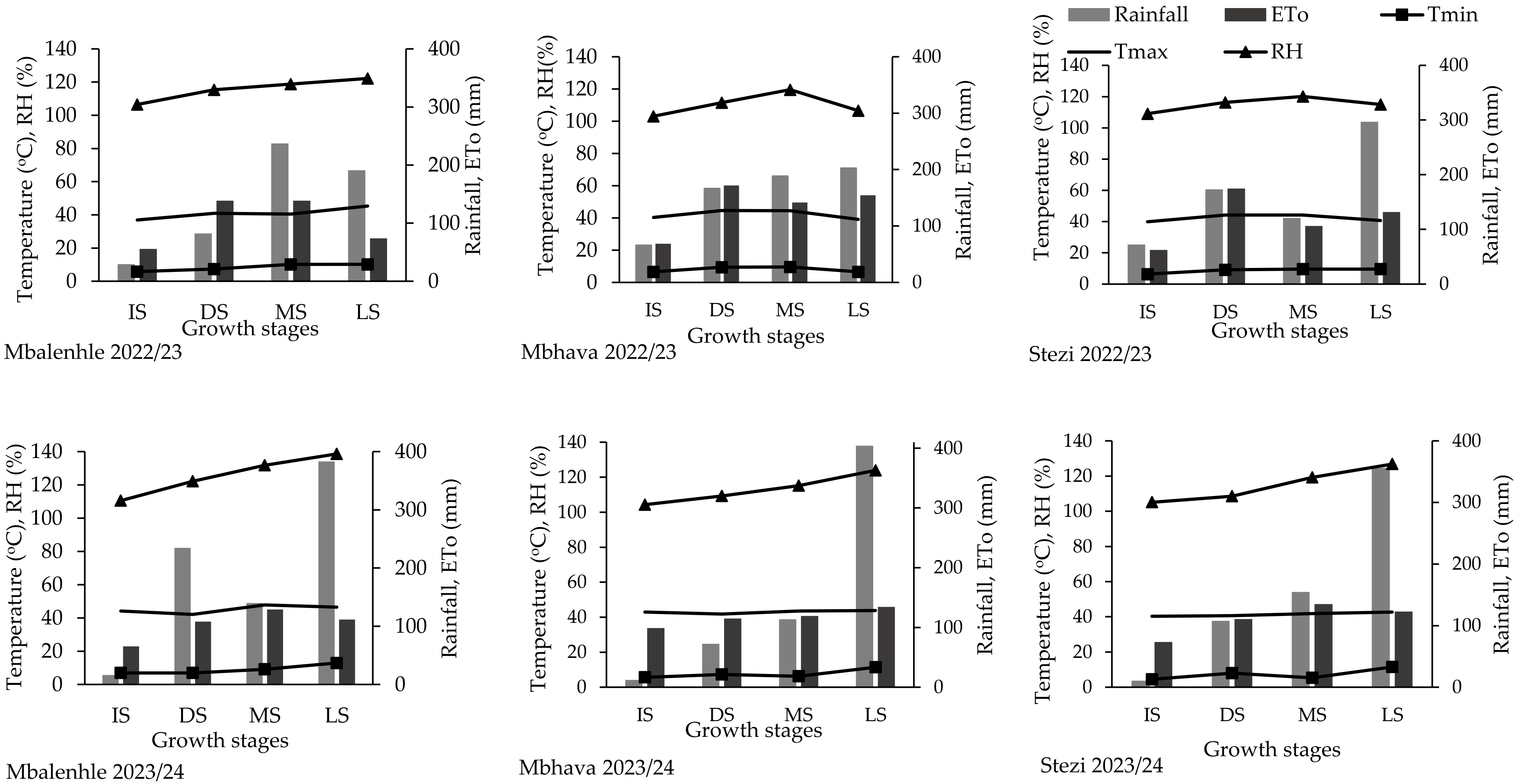

Figure 1. Weather data [rainfall, relative humidity (RH), reference evapotranspiration (ETo), and air temperature] distribution according to growth stages [initial stage (IS), development stage (DS), mid-season stage (MS) and late season stage (LS)] of the two growing seasons (2022/23 and 2023/24), for Mbalenhle, Mbhava and Stezi.

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Table 4. Daily average vapor pressure deficit across two growing seasons (kPa day^{-1}).

Locality	2022/23 Season	2023/24 Season
Mbalenhle	0.78	0.74
Mbhava	1.08	1.14
Stezi	0.82	0.83

3.2. Seasonal Variation in Crop Water Productivity

There were highly significant (p<0.001) variations in water productivity (WP) between seasons (Table 5), where WP was higher in the 2023/24 season (9.70 kg m^{-3}) compared to the 2022/23 season (8.32 kg m^{-3}) (Figure 2A). The variations in seasonal water productivity were driven primarily by highly statistically significant (p< 0.001) differences in crop water use (ET) between seasons since yields were statistically similar across seasons (p = 0.556) (Table 5). Crop water use was significantly higher in the 2022/23 season (486.85 mm), and lower during the 2023/24 season (415.07 mm) (Figure 2E), while yields were 39.36 t ha^{-1} and 39.97 t ha^{-1} (Figure 2B). Water Productivity was significantly and negatively correlated (r= -0.6) with ET (Table 6) therefore, increased crop water use resulted in a decrease in potato WP. Hence, the results indicate that high water use does not necessarily improve potato WP but can result in increased actual crop evapotranspiration, where more water is lost to the atmosphere rather than being used for plant growth [34]. The differences in ET have been caused by rainfall. There were highly significant (p< 0.001) variations where rainfall received was higher in the 2022/23 season (572.77 mm) compared to the 2023/24 season (533.42 mm) (Figure 2F), this can be further explained by the strong correlation (r= 0.89) between rainfall and ET. During the mid-season which is the critical stage where potatoes are bulking and Kc is high meaning water demand is high the 2022/23 season had higher rainfall (182 mm) compared to the 2023/24 season with 136 mm (Figure 3), this further elaborates that at this stage the 2023/24 season used water efficient according to crop needs able to utilize lower rainfall received with no water stress observed. Potato maximum canopy cover (CCx) and duration of CCx were significantly higher (p< 0.001), during the 2023/24 season (90.1% days) compared to the 2022/3 season (80.5%) (Figure 3H).

The higher CCx in the 2023/24 season resulted in a bigger transpiring canopy however that did not significantly affect the soil water content due to irregular and uneven rainfall. Understanding the influence of these variables on potato WP is crucial for farmers to improve management practices. The results revealed that water use and rainfall had significantly influenced WP, hence use efficiently of these variables under rainfed conditions by adopting practices that conserve and regulate soil moisture might lead to increased potato WP.

Table 5. Seasonal ANOVA summary table for assessed parameters over two production seasons.

Source of variation	**[1]CCx**	**Duration of CCx**	**[2]SWCP**	**[3]ET**	**Yield**	**[4]SWCH**	**Rainfall**	**[6]WP**
Season (S)	<0.001	<0.001	<0.001	<0.001	0.556	0.001	<0.001	<0.001

[1]Maximum canopy cover, [2]soil water content at planting, [3]crop water use/evapotranspiration, and [4]soil water content at harvest, and [6]water productivity.

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Table 6. Seasonal correlation of measured parameters across localities.

Source of variation	CCx	Duration of CCx	ET	Yield	SWCP	Rainfall	SWCH	WP
¹CCx	1	0.35***	0.59***	0.064ns	-0.29***	0.44***	-0.01ns	-0.12ns
Duration of CCx		1	0.34***	0.2178*	-0.13ns	0.23**	0.009ns	-0.11ns
²ET			1	0.08ns	0.03ns	0.89***	0.05ns	-0.60***
Yield				1	-0.50***	0.10ns	-0.45***	0.70***
³SWCP					1	-0.03ns	0.90***	-0.48***
Rainfall						1	0.11***	-0.53***
⁴SWCH							1	-0.1ns
⁵WP								1

[1]maximum canopy cover, [2]water use, [3]soil water content at planting, [4]soil water content at harvest, and [4]water productivity; ns, not significant; *, (p<0.05); *** ,(p<0.001).

3.3. Soil Moisture Content, Rainfall, and Water Use

The integration of cultivar, mulch, and locality had an insignificant (p>0.05) effect on rainfall, and soil water content (SWC) at planting, meanwhile, SWC at harvest was statistically affected by this integration for both seasons. Furthermore, ET was altered by the integration of cultivars, mulch, and locality for the 2023/24 season only. The secondary integration which was cultivar x locality (Tables 7 and 8) significantly affected rainfall, SWC, and ET and the results showed consistency over the growing seasons. Soil water content at planting was not influenced by mulch and cultivars, only the locality had a significant effect because mulch was not yet applied, and plants haven't emerged from the soil. This further shows that the locality had different soil properties (Table 3) and climates (Figure 1) leading to different SWCs. Mulch and rainfall increased SWC at harvest, considering that rainfall was recorded according to cultivar physiological maturity, hence late maturing cultivar Panamera (Table 1) had higher SWC at harvest ranging from 404.19 to 504.4 mm due to the high rainfall received late in the season, therefore SWC was direct proportionally to the received rainfall. Sababa with mulch or not mulch Across the locality had lower SWC at harvest since this cultivar matured earlier than other cultivars when rainfall was low (422.87 to 622.78 mm) which reduces SWC.

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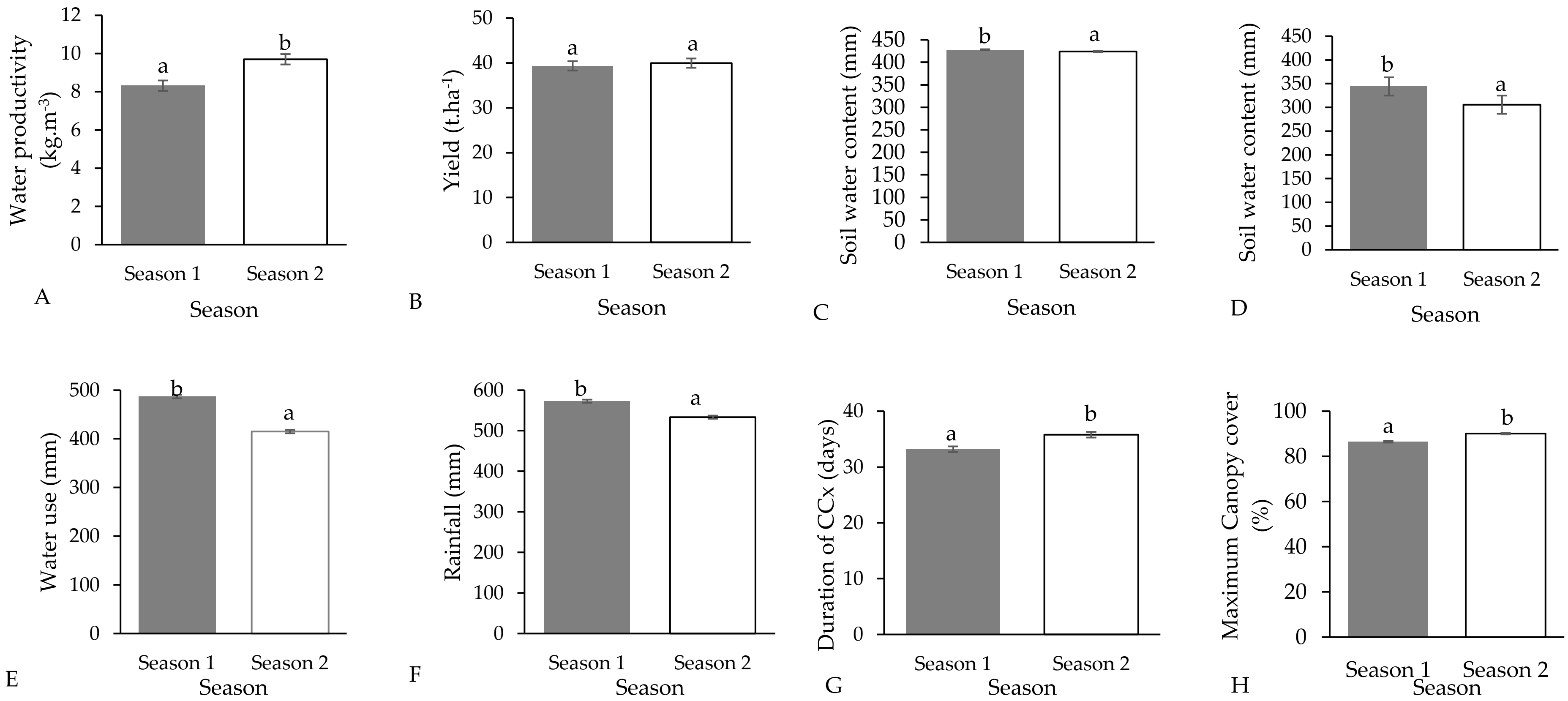

Figure 2. Seasonal measured variables, water productivity (A), yield (B), soil water content at harvest (C), soil water content at planting (D), water use (E), rainfall (F), duration of maximum canopy cover (G) and maximum canopy cover (H).

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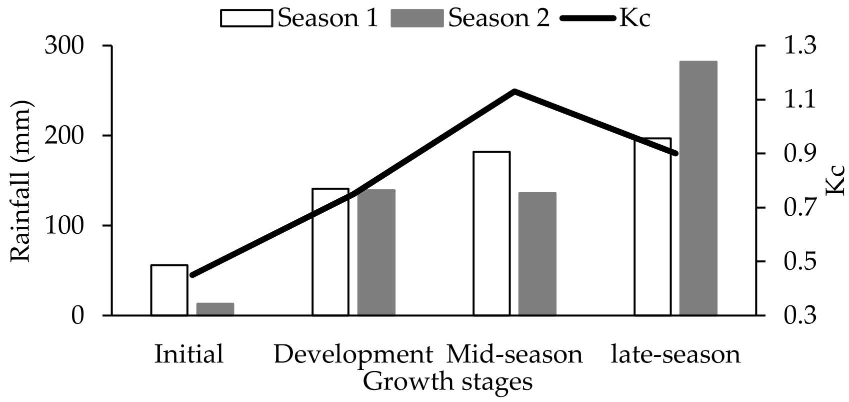

Figure 3. Seasonal rainfall distribution according to growth stages for season 1 (2022/23) and season 2 (2023/24).

Table 7. Rainfall received, soil water content (SMC) at planting at harvest, and crop water used for the 2022/23 season.

Locality	Cultivar	Mulching	Rainfall	SMC at planting	SMC at harvest	Water use
				mm		
Mbalenhle	Electra	Mulch	446.6ab	312.79a	393.35cde	409.04ab
	Mondial		486.27abc	309.42a	400.62ef	379.80a
	Panamera		501.13bc	310.81a	406.76ef	444.36b
	Sababa		433.07a	309.5a	370.62ab	398.34ab
	Electra	Not mulch	433.67a	315.49a	385.28bcd	419.81ab
	Mondial		489.60abc	307.11a	397.26def	380.84a
	Panamera		516.13c	309.21a	399.01cdef	450.51bc
	Sababa		440.67ab	311.48a	365.61a	379.54a
Mbhava	Electra	Mulch	622.78de	407.8b	504.94hi	525.63def
	Mondial		623.18de	409.71b	505.36i	527.53def
	Panamera		624.08de	410.77b	504.41i	530.44def
	Sababa		622.78de	416.17b	496.34ghi	407.60ab
	Electra	Not mulch	622.78de	411.29b	496.3ghi	537.76def
	Mondial		623.18de	413.99b	493.65ghi	543.52def
	Panamera		624.78de	411.27b	489.22gh	546.82def
	Sababa		622.78de	409.33b	488.52g	436.71b
Stezi	Electra	Mulch	586.03d	309.46a	403.89ef	517.76de
	Mondial		636.96de	312.76a	410.6f	565.29ef
	Panamera		663.33e	310.81a	404.19ef	570.35ef
	Sababa		600.3de	309.5a	384.43bcd	526.76def
	Electra	Not mulch	612.20de	311.15a	395.02cde	503.55cd
	Mondial		636.96de	307.11a	394.95cde	575.29f
	Panamera		663.53e	309.21a	396.11cdef	576.63f
	Sababa		613.60de	311.48a	381.34bc	530.43def
CV (%)			3.70	1.00	1.10	3.60
LSD (5% level)			35.06	5.76	7.94	29.10

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p-value	Cultivar x Locality	<0.001	0.0155	<0.001	<0.001

Alphabet in columns that are not the same are significantly different at p<0.05.

The higher ET was observed for Panamera ranging from 373.29 to 630.22 mm, the highest (630.22 mm) was under not mulch in Mbalenhle, meanwhile, Sababa used less water (325.26 to 530.43 mm) under mulch and not mulch across localities. Furthermore, it was interesting to note that mulch reduced cultivars water used in some cases with 1.34 to 3.37% due to reduced soil evaporation. Chen et al. [35] reported potato ET of 216.5 to 278.3 mm under rainfed conditions, meanwhile, the current study ET was in harmony with Karam et al. [36] who reported 498.5 to 606.0 mm. The high seasonal rainfall received in this study resulted in higher ET compared to other studies conducted under rainfed conditions, also the type of management practices that were used and climatic conditions resulted in different potato ET. In the current study observed results indicate climatic variability from localities emphasizing macro and microclimate variability, influencing ET. Meanwhile, within Swayimane agroecological zone, there were differences in crop water used due to differences in soil texture and rainfall received.

Table 8. Rainfall received, soil water content (SMC) at planting at harvest, and crop water used for the 2023/24 season.

Locality	Cultivar	Mulching	Rainfall	SMC at planting	SMC at harvest	Water use
				mm		
Mbalenhle	Electra	Mulch	572.87efgh	252.86a	387.43abcd	438.3cde
	Mondial		623.4h	255.46ab	398.89bcd	479.97e
	Panamera		774i	250.21a	406.67cd	617.54f
	Sababa		527.87cdefg	250.49a	383.83abc	394.53abcd
	Electra	Not mulch	572.87efgh	253.53a	381.14abc	445.26de
	Mondial		623.87h	252.58a	393.53abcd	482.92e
	Panamera		774i	256.69ab	400.46bcd	630.22f
	Sababa		547.4defgh	251.77a	379.95ab	419.22bcde
Mbhava	Electra	Mulch	465.17abc	390.67g	489.22ef	366.62abcd
	Mondial		435.53ab	388.25g	478.41ef	345.38ab
	Panamera		592.63gh	388.27g	503.83f	477.07e
	Sababa		422.87a	388.92g	486.52ef	325.26a
	Electra	Not mulch	455.13abc	388.13g	482.37ef	360.89abc
	Mondial		468.47abcd	387.71g	475.08e	381.1abcd
	Panamera		582.63fgh	389.29g	494.53ef	477.39e
	Sababa		422.87a	391.18g	475.26e	338.78a
Stezi	Electra	Mulch	495abcde	283.03g	397.2bcd	380.83abcd
	Mondial		486.63abcd	266.75bc	403.96bcd	349.42ab
	Panamera		512.7bcdef	274.3cdef	412.97d	374.03abcd
	Sababa		451.57abc	279.79def	382.77abc	348.59ab
	Electra	Not mulch	495abcde	280.4rf	392.52abcd	382.88abcd
	Mondial		516.13cdefg	269.59cde	394abcd	391.73abcd

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	Panamera	512.7bcdef	267.04bcd	406.45cd	373.29abcd
	Sababa	470.87abcd	278.93cdef	369.33a	380.46abcd
CV (%)		4.7	1.3	1.9	6.2
LSD (5% level)		41.39	6.73	13.48	41.94
p-value	Cultivar x Locality	<0.001	<0.001	0.003	<0.001

Alphabet in columns that are not the same are significantly different at p<0.05.

3.4. Yield

The integration of locality x cultivar had a significant ($p<0.05$) effect on yield for both years showing consistency. Meanwhile, locality x cultivar x mulch had an insignificant ($p>0.05$) effect on yield for both seasons, hence the important integration for yield was cultivar x locality. The insignificant effect of mulch solo was deprived by the high received rainfall, results reveal that rainfall distribution in 2022/23 was almost matching Kc (Figure 3), such that water availability induces the role of mulch to plots that did not have mulch, moisture was sufficient in the soil to meet crop water demand. Whereas, in the 2023/24 season rainfall was more erratic with frequent dry spells hence mulch plays a significant role in conserving soil moisture, hence mulch solo had a statistically significant effect on yield, however when it was integrated had an insignificant effect. The integration of cultivar and locality resulted in potato yield ranging from 23.90 to 63.60 t ha^{-1} Figure 4, Electra kept overperforming over the two-growing season across locality yield ranging from 33.55 to 63.6 t ha^{-1}, with the highest yield in Mbalenhle. Within Swayimane agroecological, Mbhava was found to have a low yield for all cultivars ranging from 23.90 to 47.54 t ha^{-1} compared to Stezi (31.84 to 59.98 t ha^{-1}), nevertheless, Appelsbosch agroecological had the highest cultivar yield ranging from 34.41 to 63.60 t ha^{-1} compared to Swayimane. Waqas et al. [37] reported potato yield of 29.44 to 49.65 t ha^{-1} which is within the range of the current study, furthermore Das et al. [38] reported lower yields of different cultivars compared to the current study ranging from 14.08 to 33.54 t ha^{-1}. The variation observed from these different studies is attributed to climatic differences of the agroecologies where the study was conducted, cultivars have different yield potentials and have different genetic modifications, and lastly, the practices management were different.

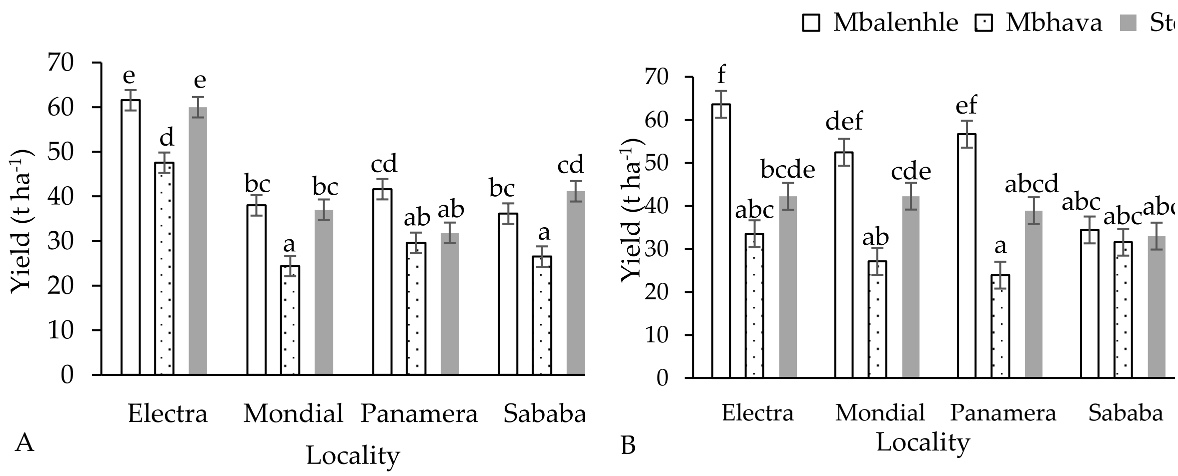

Figure 4. Yield influenced by the integration of location and cultivar for the 2022/23 (A) and 2023/24 (B) seasons.

Furthermore, the current study result revealed that micro-climate variation had attributed to yield differences observed in localities. For instance, Mbhava's higher average daily vapor pressure deficit (VPD) (1.08-1.14 kPa) (Table 4) compared to Stezi (0.82 and 0.83) and Mbalenhle (0.78 and 0.74) leads to a higher difference in atmospheric dryness [15], increasing water loss through higher

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transpiration (especially in C3 plants where stomatal control is not highly regulated). Also, higher elevations (Mbalenhle and Stezi) are on the sun-facing (north-facing) slope, more exposed to direct sunlight thereby improving plants' photosynthesis compared to Mbhava which is on the south-facing slope. Furthermore, rainfall received on conservative days had a negative effect on the clay soils for Mbhava, compared to Stezi and Mbalenhle have sandy soils with higher drainage. Overall, Panamera and Electra were able to maintain the prolonged duration of CCx (Figure 5) resulting in higher yield due to the long-maintained vegetative stage that will allow Panamera and Electra to accumulate more dry matter and increase tuber size.

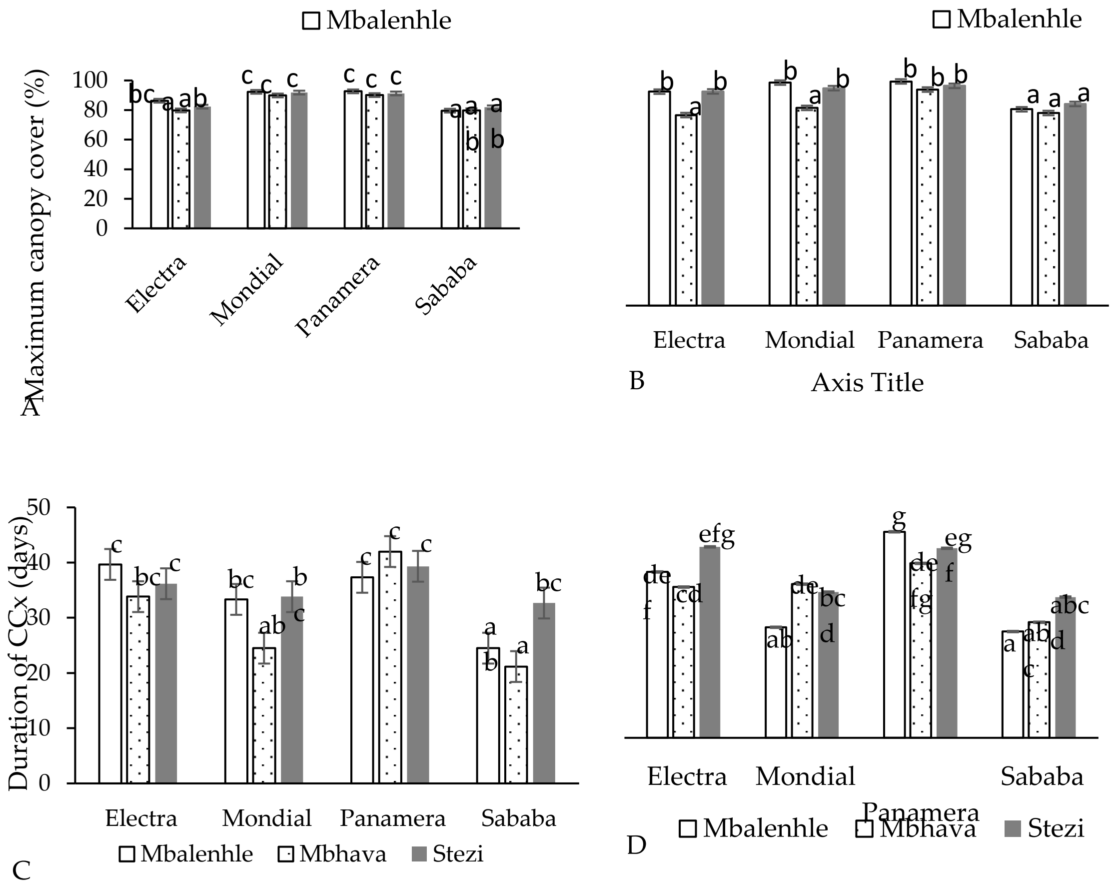

Figure 5: Maximum canopy cover (CCx) of selected cultivars across localities [(A) 2022/23 and (B) 2023/24] and duration of CCx [(C) 2022/23 and (D) 2023/24].

3.5. Water Productivity

Water productivity (WP) was significantly ($p<0.001$) affected by cultivar x locality (for both seasons), whereas three-way integration (cultivar x mulch x locality) was found insignificant for WP. Water productivity was found to be directly proportional to yield and decreases with increased ET. Mulch solo was found to be significantly ($P<0.001$) affecting ET and yield as mentioned above in the 2023/24 season, hence WP was also influenced. The WP obtained from this study ranged from 4.56 to 14.53 kg m^{-3}, Electra in Mbalenhle being on the upper range and showing consistency over the two growing seasons, and the lowest WP was observed in Mbhava for Mondial (4.56 kg m^{-3}). Mthembu et al. [22] reported WP of 1.09 to 5.09 μmolCO_2 $mmol^{-1}$ H_2O as instantaneous water use efficiency at different growth stages. Meanwhile, Lindi et al. [2] and Ijaz-ul-Hassan et al. [3] reported potato WP that was in line with the current study 3.56 to 8.70 kg m^{-3} and 14.60 to 17.28 kg m^{-3} respectively. The variation between these WP is attributed to different actual water used by cultivars and the yield

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which was influenced by soil type, management practices, and climatic conditions considering these studies conducted under different environments.

As mentioned above rainfall in the 2023/24 season was more erratic, such that WP was more influenced by ET rather than yield. A high amount of rainfall was received in the late-season stage, for instance, Sababa is an early-maturing cultivar and uses less water compared to late-maturing cultivars that utilize late-season rainfall. Furthermore, climatic conditions such as low VPD, and high relative humidity of Stezi and Mbalenhle micro-climates affected ET positively by lowering atmospheric water demand, consequently resulting in higher yield which translate to higher WP. This was the opposite in Mbhava, higher VPD led to atmospheric dryness decreasing the relative humidity and resulting in ET being dominated by evaporation, hence the available water was not contributing to making yield but went to the atmosphere. It is worth noting that localities that are in high elevation with sandy soil texture (Mbalenhle and Stezi) showed a more stable response between years for WP. The only source of water in these agroecologies is rainfall which showed uneven distribution and put resource-constrained potato farming at risk. Therefore, to be resilience and improve WP, under these conditions, the selection of cultivars that use less water and produce high yield are low-hanging fruits for improving potato WP, and climatic conditions that have proportionality of rainfall and crop coefficient, with less atmospheric dryness is very important.

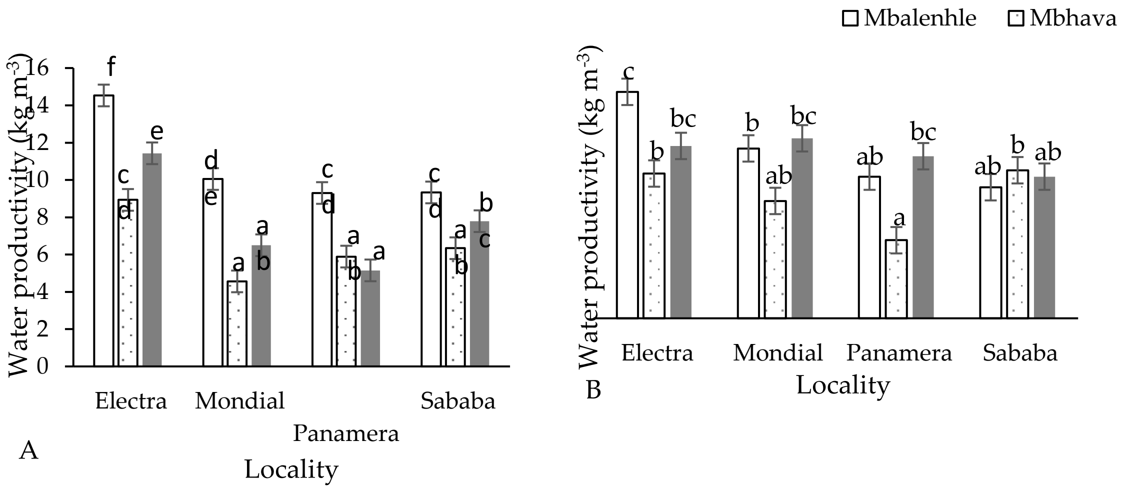

Figure 6. Water productivity influenced by the integration of locality and cultivar for 2022/23 (A) and 2023/24 (B) seasons.

4. Conclusions

The influence of rainfall, soil water content, canopy development, and water used, suggest that potato WP can be increased by applying practices that conserve soil moisture, considering the risks of climatic variability. The three-way integration of cultivar selection, locality, and mulch application did not statistically alter rainfed potato water productivity, since mulch inclusion did not yield advantage under high-rainfall seasons observed during the 2022/23 and 2023/24 growing periods. We postulate that the three-way interaction of cultivar selection, locality, and mulch application may significantly alter rainfed potato water productivity given low-rainfall seasons where potatoes may be subjected to water scarcity and drought stress. However, the secondary integration of cultivar selection and locality significantly altered potato water productivity in both seasons. Planting the Electra cultivar in Appelsbosch consistently yielded significantly high water productivity across both planting seasons. Out of the three drought-tolerant cultivars (Electra, Mondial, and Sababa), Electra showed good yield performance even under dry spells that experienced, and WP stability across agroecologies. Appelsbosch high humidity, reduced atmospheric dryness, lowered unproductive losses (evaporative) and stressful conditions, thereby high yield returns per water used. Micro-climatic (Stezi and Mbhava) had unexpected results of statistically superior WP in Stezi compared to Mbhava, also higher VPD in Mbhava lower WP through increasing unproductive losses. Electra is

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recommended for production in these zones due to water productivity stability in various agroecologies and WP was mainly caused by higher yield. Considering the even distribution of rainfall shifting of planting dates can be an option to make use of late-season rainfall.

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