WATER USE EFFICIENCY OF TARO (*Colocasia esculenta*) UNDER VARYING WATERING REGIMES AND PLANTING DENSITIES IN EMBU, KENYA †

[EFICIENCIA EN EL USO DEL AGUA DEL TARO (*Colocasia esculenta*) BAJO VARIOS REGÍMENES DE RIEGO Y DENSIDADES DE PLANTACIÓN EN EMBU, KENIA]

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SUMMARY

Background. Taro (*Colocasia esculenta*) can be grown in a variety of environmental and edaphic conditions, but it is most typically grown in wetlands. The optimal conditions for its growth are two water regimes i.e., waterlogged or flooded conditions to dryland or unflooded conditions. An important criterion in crop yield is water use efficiency (WUE), and it has been suggested that crop production per unit of water used can be increased. **Objectives.** To determine the WUE of taro in Kenya's sub-humid environment under different watering regimes and planting densities. **Methodology.** A study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) – Embu Research Centre, during the long rains (LR) 2021, short rains (SR) 2021/2022, and long rains (LR) 2022. A factorial experiment with a split-plot layout arranged in a completely randomized block design was used. The main factor was the irrigation levels while the sub-factor was the planting density, with three replications. The three irrigation levels were at 100 %, 60 %, and 30 % based on the field capacity (FC). The planting densities used were 0.5m × 0.5m (40,000 plants ha^{-1}), 1m × 0.5m (20,000 plants ha^{-1}), and 1m × 1m (10,000 plants ha^{-1}), representative of high, medium, and low planting densities respectively. **Results.** The WUE was influenced by season and watering regime ($P < 0.05$). The 30% FC had the highest WUE with the 100 % FC having the lowest. The high WUE under 30 % FC (19.40 kg $ha^{-1}mm^{-1}$) was associated with the high biomass (1.97 kg) and low water use (2269.41 mm) recorded under limited water conditions. The medium (1m × 0.5m) planting density attained the highest WUE (12.16 kg $ha^{-1}mm^{-1}$) with the high planting density (0.5m × 0.5m) having the lowest (10.65 kg $ha^{-1}mm^{-1}$), though no significant differences were recorded. **Implications.** The varying watering regimes and planting densities in this study have different capacities to utilize the supplied water. The total taro biomass increased with decrease in water supplied and in turn maximized the water use efficiency. **Conclusion.** To achieve the highest yield per unit of water consumed, a watering regime of 30 % FC and a planting density of 1 m × 0.5 m (20,000 plants ha^{-1}) is recommended.

Key words: water use efficiency; irrigation; planting density; yields.

RESUMEN

Antecedentes. La malanga (*Colocasia esculenta*) se puede cultivar en una variedad de condiciones ambientales y edáficas, pero generalmente se cultiva en humedales. Las condiciones óptimas para su crecimiento son dos regímenes de agua, es decir, condiciones anegadas o inundadas o condiciones de tierras secas o no inundadas. Un criterio importante en el rendimiento de los cultivos es la eficiencia en el uso del agua (WUE), y se ha sugerido que se puede aumentar la producción de cultivos por unidad de agua utilizada. **Objetivos.** Determinar la WUE del taro en el ambiente subhúmedo de Kenia bajo diferentes regímenes de riego y densidades de plantación. **Metodología.** Se realizó un estudio en la Organización de Investigación Agrícola y Ganadera de Kenia (KALRO) - Centro de Investigación Embu, durante las lluvias largas (LR) 2021, lluvias cortas (SR) 2021/2022 y lluvias largas (LR) 2022. Se realizó un experimento factorial con arreglo de parcelas divididas en un diseño de bloques completamente al azar. El factor principal fueron los niveles de riego mientras que el subfactor fue la densidad de siembra, con tres repeticiones. Los tres niveles de riego fueron al 100 %, 60 % y 30 % de la capacidad de campo (FC). Las densidades de siembra utilizadas fueron 0.5m × 0.5m (40,000 plantas ha^{-1}), 1m × 0.5m (20,000 plantas ha^{-1}), y 1m × 1m (10,000 plantas ha^{-1}),

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representativas de plantaciones con alta, media y baja densidad respectivamente. **Resultados.** La WUE estuvo influenciada por la estación y el régimen de riego ($P < 0.05$). El 30 % FC tuvo la WUE más alta y el 100 % FC tuvo la más baja. La alta WUE bajo 30 % FC (19.40 kg $ha^{-1}mm^{-1}$) estuvo asociada con la alta biomasa (1.97 kg) y el bajo uso de agua (2269.41 mm) registrado bajo condiciones de agua limitada. La densidad de plantación media (1m × 0.5m) alcanzó la WUE más alta (12.16 kg $ha^{-1}mm^{-1}$) y la densidad de plantación alta (0.5m × 0.5m) obtuvo la más baja (10.65 kg $ha^{-1}mm^{-1}$), aunque no se registraron diferencias significativas. **Implicaciones**. Los diferentes regímenes de riego y densidades de siembra tienen diferentes capacidades para utilizar el agua suministrada. La biomasa total de taro aumentó con la disminución del suministro de agua y, a su vez, maximizó la eficiencia del uso del agua. **Conclusión.** Para lograr el mayor rendimiento por unidad de agua consumida, se recomienda un régimen de riego de 30 % FC y una densidad de plantación de 1 m × 0.5 m (20,000 plantas ha^{-1}).

Palabras clave: eficiencia de uso de agua; riego; densidad de siembre; rendimiento.

INTRODUCTION

One of Kenya’s underutilized crops is taro (*Colocasia esculenta* (L.) Schott), which is primarily cultivated, by women in subsistence farmer systems for its fleshy corms and nutritious leaves. Taro also serves as a buffer crop when other staple foods are in low supply (Ngetich *et al.,* 2015). It is mainly grown in riverbeds and is referred to as arrowroot or *nduma*. The riverbeds, however, are already a limited resource in the face of climate change and especially during times of water scarcity (Wambugu and Muthamia, 2009; Akwee *et al.*, 2015; Ngetich *et al.*, 2015). Taro can be cultivated on moisture beds that are lined with a polyethylene sheet in upland farming to prevent water loss through its percolation into the soil (Oxfarm, 2021). Water must be consistently available throughout the growing season to prevent water stress, which can lead to the development of poor-quality, malformed corms (Sibiya, 2015; Ansah, 2016).

There is little data on using supplemental irrigation to increase taro productivity per amount of land being cultivated. The agronomy of taro and its contribution to food security and sustainability are also little understood. To define water use and its limits under field conditions and to understand how taro responds to water shortages, precise water applications are crucial (Odubanjo *et al.,* 2011). To improve crop growth under irrigation, it is essential to figure out how much water to use and when to irrigate to obtain the best water use efficiency (Kang’au *et al.*, 2011). As a result, efficient irrigation will aid in enhancing and maintaining crop productivity while preserving water and soil nutrients (Sijali, 2001).

When used over a time scale of days, development stages, or growth seasons, water use efficiency of productivity (WUEp) is described as the kilograms of biomass generated per applied cubic meter of water (de Pascale *et al.*, 2011). The WUEp takes into account the quantity of plant yields per unit volume of water consumed across a given land area as well as the quantity of plant yields per unit of water lost through evapotranspiration during growth (Caviglia and Sadras, 2001; Koech *et al.,* 2015). WUEp has been used to suggest that rainfed crop production per unit of water consumed can be increased because it is a key factor in determining crop yield under stress (Blum, 2009). Agriculture should prioritize improving water use efficiency, shifting the emphasis from increasing production per unit of land area to increasing productivity per unit of water consumed. Water must be conserved, and crop growth must be maximized, to maximize WUEp (de Pascale *et al.,* 2011).

Kenya has experienced severe water shortages for many years, primarily as a result of years of repeated droughts, poor water supply management, and pollution of scarce water resources (Marshall, 2011). Moreover, Kenya is one of the world’s water-scarce nations, which has led to a decline in crop productivity over time (Mulwa *et al.,* 2021). By supplying the needed water resources directly to the plant, drip irrigation reduces water demand and decreases water evaporation losses during times of drought and water scarcity (Sijali, 2001; UNEP, 2013). This has a favourable impact on WUE in irrigated crop areas, demonstrating the need of increasing the WUEp in the management of irrigation water (Hatfield and Dold, 2019). Additionally, the irrigation efficiency is as high as 95 % under drip while it is 30-50 % under surface irrigation, making drip irrigation an effective strategy for increased irrigation and water use efficiency (Ngigi, 2009; Khan *et al.,* 2019). Early in the growing season, the adoption of a micro-irrigation system reduces soil water evaporation from between plant rows and limits almost all canopy evaporation. These changes demonstrate that WUE can be changed through system water management by improving WUEp in irrigated crop areas (Hatfield and Dold, 2019).

Several methods can help decide when to irrigate or the irrigation schedule. The soil moisture depletion approach is most relevant to this study as it involves the determination of the amount of moisture present in the root zone (AgriInfo, 2018). Soil moisture sensors are useful in the determination of soil moisture as the measurements are in real-time (Subir *et al.,* 2011). It is crucial to periodically measure soil moisture where irrigation is used to know the soil moisture status and determine how much water to apply. Water management has become crucial with the evolution of irrigation-based farming, emphasizing the requirement to evaluate soil water content and plants' consumption of water (Onoja *et al.*, 2014). Using water use efficiency in irrigation planning and decision-making will facilitate efficient water management that will improve yields (Vieira *et al.*, 2018). As such, it is crucial to understand the WUEp of taro in Kenya’s sub-humid environment under different watering regimes and planting densities.

MATERIALS AND METHODS

Study Site Description

The research was carried out at the Kenya Agricultural and Livestock Research Organization (KALRO) – Embu Research Centre for three growing seasons: long rains (LR) 2021, short rains (SR) 2021/2022, and long rains (LR) 2022 (Figure 2). Embu County is situated between latitudes 0^0 8’ and 0^0 50’ South and longitudes 37^0 3’ and 37^0 9’ East (Kangai et al., 2021) (Figure 1). The Research Centre receives 1250 mm of annual rainfall in two rainy seasons, namely, March to May (long rainy season) and October to December (short rainy season). The temperature ranges from 12°C in July to 30°C in March and September, with a mean temperature of 21° C. The soils are mostly clay, deep, well-drained, and have a strong structure (Kisaka *et al.*, 2015; Embu County Government, 2019). According to the IUSS Working Group's WRB (2015) classification, the soils are classified as Eutric Nitisols. Table 1 displays the physical and chemical characteristics of the soil. The composite soil samples were analyzed using standard methods as described in Okalebo *et al.* (2002). Using a soil auger, several disturbed subsamples were collected at various points in a *zig-zag* pattern to ensure homogeneity within the experimental plot area. The sub samples were then mixed thoroughly to make a composite sample in a bucket and placed in a zip-lock bag. The samples were then dried before being placed in a container and sent to the laboratory for chemical analysis and soil texture determination. Undisturbed soil samples were collected using core rings and sent to the laboratory for determination of saturated hydraulic conductivity. Total nitrogen is very low (0.09%), phosphorous is moderate (50.75 mg kg^{-1}) and potassium is high (624 mg kg^{-1}), all of which are important for crop growth (Msanya *et al.*, 2001). The soil has a pH of 5.12, slightly acidic and the ideal pH for the growth of taro (Onwueme, 1999). Using the Soil Water Characteristics Hydraulic Properties Calculator (https://hrsl.ba.ars.usda.gov/soilwater/Index.htm), the soil texture analysis were used to calculate the field capacity (FC), and permanent wilting point (PWP) (Table 1). For use in watering taro, the irrigation water’s quality was evaluated (Table 2). The irrigation water was analyzed for pH, electrical conductivity (EC), chlorides, sulphates, fluorides, sodium (Na$^+$), magnesium (Mg^{2+}) and potassium (K$^+$), calcium (Ca^{2+}), and alkalinity (Katerji *et al.*, 2003). The quality of the irrigation water meets the standards for irrigation water (FAO, 1994; Republic of Kenya, 2006).

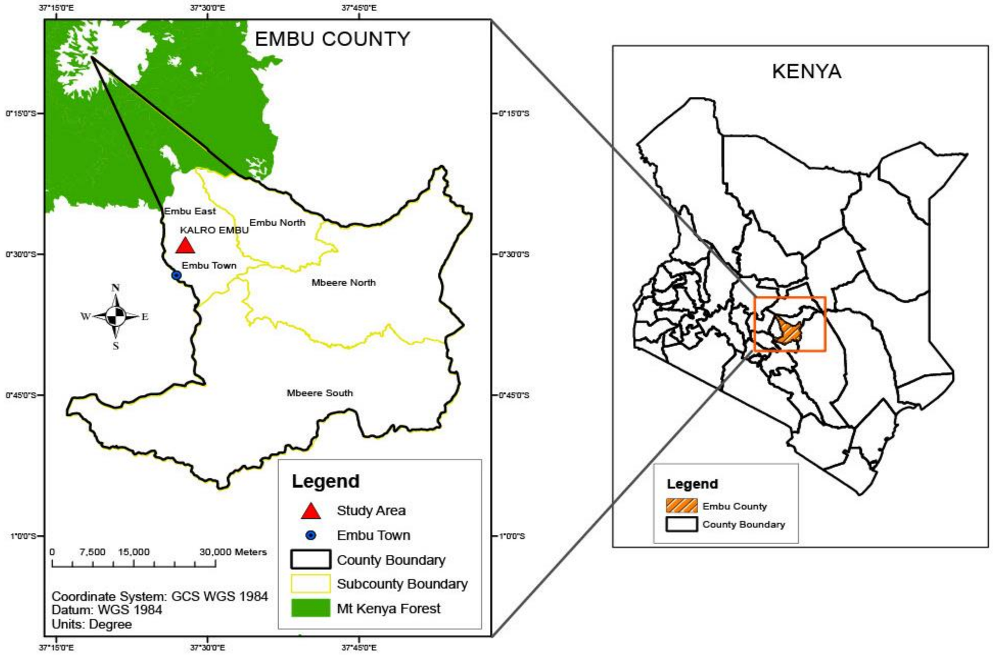

Figure 1. Location of the Study Site, KALRO – Embu, Kenya (Generated from ArcGIS)

Table 1. Baseline physical and chemical soil properties of the experimental site (0 - 30cm) at KALRO Embu, Kenya

Soil Property	Value	Soil Property	Value
Chemical properties			
pH	5.12	Manganese (mg kg $^{-1}$)	143.50
Organic Carbon (%)	2.10	Physical Properties	
Total Nitrogen (%)	0.09	Bulk Density (g cm^{-3})	1.06
Phosphorous (mg kg $^{-1}$)	50.75	Sand (%)	42.0
Potassium (mg kg $^{-1}$)	624.0	Silt (%)	16.0
Calcium (mg kg $^{-1}$)	700.0	Clay (%)	42.0
Zinc (mg kg $^{-1}$)	51.70	Textural Class	Clay
Sodium (mg kg $^{-1}$)	26.45	Saturated Hydraulic Conductivity (Ksat) (cm hr^{-1})	13.36
Iron (mg kg $^{-1}$)	32.15	Permanent Wilting Point (PWP) (% volume)	16.0
Magnesium (mg kg $^{-1}$)	154.80	Field Capacity (FC) (% volume)	37.8

Table 2. Irrigation water chemical analysis in the experimental site at KALRO Embu, Kenya.

Parameter	Value	Parameter	Value
pH	6.8	Chlorides (mg L^{-1})	30.96
EC (uS cm^{-1})	400	Sulphates (mg L^{-1})	6.15
Potassium (mg L^{-1})	4.52	Magnesium (mg L^{-1})	2.3
Sodium (mg L^{-1})	14.7	Fluoride (mg L^{-1})	0.40
Calcium (mg L^{-1})	0.89	Alkalinity (mg L^{-1})	13

Experimental Layout

A factorial experiment with a split-plot layout arranged in a completely randomized block design was used. The main factor was the irrigation levels (whole plots) while the second factor was the planting density (sub plots), with three replications. The three irrigation levels were at 100 %, 60 %, and 30 % based on the field capacity (FC). The planting densities used were 0.5m × 0.5m (40,000 plants ha^{-1}), 1m × 0.5m (20,000 plants ha^{-1}), and 1m × 1m (10,000 plants ha^{-1}), representative of high, medium, and low planting densities respectively.

Planting Material

Taro basal stems were sourced from farmers' fields in Kirinyaga County, at the beginning of the experiment. The planting materials were collected as apical 1-2 cm of the corm with basal 15-20 cm of the petioles attached. The common landrace and commercially preferred and available was the *Dasheen* variety, which is characterized by one large cylindrical main corm and is preferred by the farmers in the region.

Irrigation and moisture bed preparation

The drip system consisted of a 5000 litres tank, a water filter, a water metre, a ball valve, nine valves, nine T-joins, button drippers, start connectors, PVC pipes, L-bows, drips lines, end lines, and end caps. The tank was raised to 1.5 m and supplied water to the crop. The system also consisted of a disk filter of one-inch diameter. This filter is effective for water laden with debris, and it does not allow any particles or debris to pass through. Water was then supplied to the crop through a one-inch diameter mainline which was connected to a sub-main line, which was further connected to the drip lines within the plots. Button drippers/emitters on the drip lines supplied water to the individual plants. The end caps were fixed to terminate the water flow. The drip line spacing was dependent on the different plant spacings in each plot. The emitter discharge was 5.6 L hr $^{-1}$. Each plot was 4 m × 4 m separated by 2 m wide spacing and dug to a 0.5 m depth and lined with a 1000-gauge double-folded black polythene sheet to create a moisture bed. The polythene sheet prevented lateral water movement between plots and seepage. Manure was added to the dug-out soil from each plot in a ratio of 2:1 ratio before being added back to each plot (the moisture bed) with a 10 cm depression.

Crop coefficient (Kc) values for taro are described by Fares, (2008) whereby Kc initial is 1.05 (2 months), Kc mid-season is 1.15 (4 months) and Kc late season is 1.1 (1 month). An average Kc value of 1.2 was used. The reference crop evapotranspiration (ETo) was obtained from Embu's automatic weather station (AWS). Using the values of Kc and ETo, the crop water requirement (ETa) was calculated as described by Allen et al. (1998):

$$\text{ETa} = \text{ETo} \times \text{Kc}$$

Where ETa is crop water requirement, ETo is reference evapotranspiration, and Kc is crop factor/coefficient.

Irrigation Scheduling

Irrigation scheduling was determined using the soil moisture depletion technique (AgriInfo, 2018; Dong, 2022). This technique is more site-specific than the climatic parameter technique which is generalized and widely variable. For the first two months of the trial, all treatments were irrigated to field capacity (Table 1) to ensure good taro crop establishment. Thereafter, the watering regime treatments were applied. To ensure water availability during the day's peak demand periods, irrigation was carried out three times every week, during the mornings.

Irrigation Schedule was determined as shown in Eqn 1.

$$\text{Irrigation schedule} = \frac{Daily\ Water\ Requirement\ (l/day)}{Emitter\ Discharge\ (l/hr)} \quad (1)$$

The irrigation schedule for the 100 % FC, 60 % FC, and 30 % FC watering regimes were 22 minutes, 13 minutes, and 6 minutes respectively. After 24 hours, skipping a day, the irrigation water was applied. With the use of a water metre, the average total amount of water used for each irrigation regime was 2000 litres (30 % FC), 4000 litres (60 % FC), and 8000 litres (100 % FC).

Christiansen's Coefficient of Uniformity

The coefficient of uniformity (CU) is described as the ratio of the absolute difference of each value from the mean and the mean of means (Christiansen, 1942). The Christiansen's Coefficient of Uniformity (CU) can be expressed as in Eqn 2.

$$\text{CU} = 100\left(1 - \frac{\sum_{i=1}^{n}|xi - \mu|}{\sum_{i=1}^{n} xi}\right) \quad (2)$$

Where, n – Number of the depth measurements of the water applied, representing an equal irrigated area. Xi – measured application depth in litres (L). µ – mean application depths in litres (L). CU – coefficient of uniformity (%).

This test was conducted to determine the efficiency of the drip irrigation system. Using graduated beakers, the system was opened, and water samples were collected for 90 seconds, and thereafter the uniformity was determined to be 89 %, indicating a high efficiency in water application (Veeranna *et al.*, 2017; Darimani *et al.*, 2021).

Soil water measurements

A digital hand–held moisture sensor meter–HSM50 was used to monitor soil moisture content weekly, two months after the planting when the crop has been established until when the taro reaches the physiological tuber maturity. Moisture readings (percent water by volume) were taken from between and within the crop rows. The meter readings (% v) were converted to mm as follows (Eqn 3):

$$Soil\ moisture\ content\ (mm) = \%\,v \times SD \quad (3)$$

Where: % v is the percent soil water by volume and SD is the rooting soil depth (mm)

Determination of water use

The residual of a soil water balance as described by Allen et al. (1998) was used to compute the water use (WU) for each treatment. The water use was determined as follows (Eqn 4)

$$\text{WU} = \text{P} + \text{I} - \text{D} - \text{R} - \Delta\text{SWC} \quad (4)$$

Where: WU = water use /evapotranspiration (mm), P = precipitation (mm), I = irrigation (mm), D = drainage (mm), R = Runoff (mm), and ΔSWC = changes in soil water content (mm).

Drainage was considered to be negligible since the moisture beds were lined with polythene paper, which prevents water from seeping beyond the root zone. Runoff was negligible because the gradient in the study area was flat (< 2%). The change in soil water content (ΔSWC) was measured using moisture meter readings to give volumetric water change. Change in soil moisture content was determined using the soil moisture measurements, where the difference between the amount of water added to the root zone and that withdrawn was determined in a given time. The soil water balance was then simplified to (Eqn 5):

$$\text{WU} = \text{P} + \text{I} - \Delta\text{SWC} \quad (5)$$

Where: WU = water use = evapotranspiration (mm), P = Precipitation (mm), I = irrigation (mm), and ΔSWC = changes in soil water content (mm)

Determination of water use efficiency (WUEp)

The water use efficiency of productivity was calculated as (Eqn 6):

$$WUEp = Biomass/WU \qquad (6)$$

Where: WUEp = water use efficiency of productivity in kg ha^{-1} mm^{-1}, Biomass = above-ground biomass plus below-ground portion in kg/ha, and WU = water use/ crop evapotranspiration (mm)

Statistical Analysis

Yield and water use efficiency data collected were subjected to analysis of variance using the GenStat statistical software. Mean separation was done using the least significant difference (LSD) at a 5 % level of probability where the ANOVA *F*-values were significant.

RESULTS

Weather data

Figure 2 represents the monthly average temperature and rainfall received at the study site for the Long Rains 2021, Short Rains 2021/2022, and Long Rains 2022 growing seasons. The months of April 2021, November 2021, and April 2022 received the highest rainfall average for the first, second, and third seasons respectively. This is the second month after planting for the three seasons which is characterized by vegetative growth and corm initiation (Tumuhimbise *et al.*, 2009). Temperatures were highest in March 2021 for the first season, February 2022 for the second season, and March 2022 for the third season, and significantly cooler in July 2021, August 2021, and August 2022. A trend can be seen whereby the months of April received the highest rainfall, March the highest temperatures, and August the lowest temperatures during the three seasons of the study. Warmer temperatures (from the second to the fourth month after planting) coincided with vegetative development and corm initiation stages for the three seasons, providing optimum temperatures for taro growth.

Total Biomass and Yield of taro as influenced by watering regimes and planting density

The total biomass and yield were influenced by season and planting density ($P < 0.05$) (Table 3). The 30 % FC had the highest biomass per plant (1.97 kg) and the lowest yield (11.79 t ha^{-1}) across the three seasons. Intermediate moisture conditions (60 % FC) favoured the corm yield (12.76 t ha^{-1}). The low planting density (1 m × 1 m) favoured the biomass per plant (2.12 kg), with a decreasing trend of 1m × 1 m > 1 m × 0.5 m > 0.5 m × 0.5 m. The high planting density (0.5 m × 0.5 m) increased the corm yield (20.14 t ha^{-1}), with a trend of 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m. Additionally, there was a significant interaction between season and planting density for the total biomass and the yield ($P < 0.05$) (Table 3).

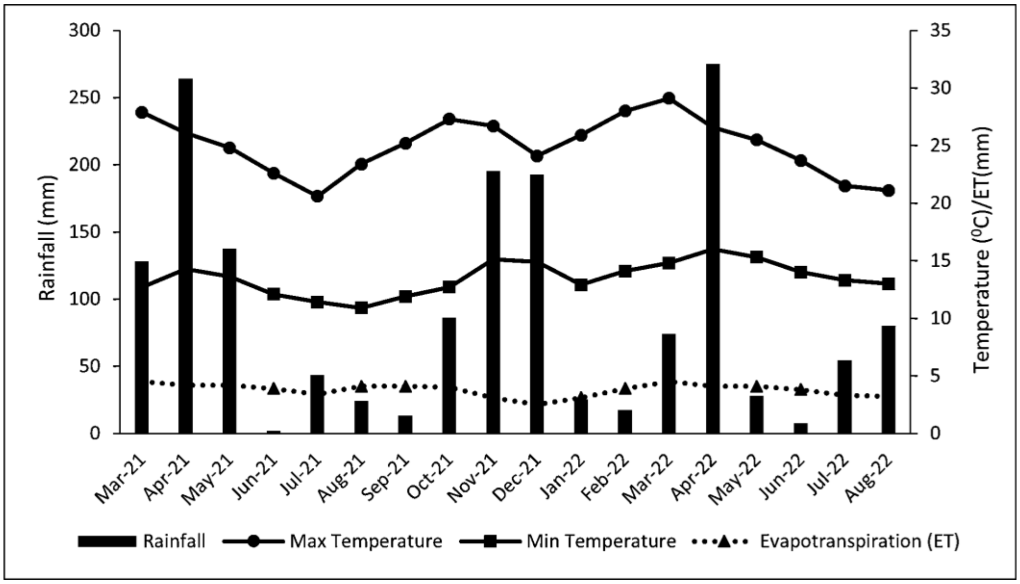

Figure 2. Monthly averages for the meteorological data during the three growing seasons (LR 2021, SR 2021/2022, and LR 2022) of taro (*Colocasia esculenta*) at KALRO, Embu, Kenya.

Water Use of taro as influenced by watering regimes and planting density

The water use was influenced by season, watering regimes, and planting density (*P < 0.001*) and there was a significant interaction between the watering regime and the planting density (*P < 0.001*) (Table 3). The second season had the highest water use (5097.43 mm) compared with the first (4874.35 mm) and third (4837.40 mm) seasons. The 100 % FC watering regime (8269.95 mm) and the 0.5m × 0.5m (40,000 plants ha^{-1}) planting density (7646.09 mm) had the highest water use values with the 30 % FC watering regime (2269.41 mm) and 1 m × 1 m (10,000 plants ha^{-1}) planting density (2678.30 mm) having the lowest (Table 3), with a trend of 100 % FC > 60 % FC > 30 % FC for the watering regime and of 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m for the planting density.

Water Use Efficiency of productivity (WUEp) of taro as influenced by watering regimes and planting density

Growing season and watering regime influenced the WUEp (*P < 0.05*) with the first season (15.11 kg ha^{-1} mm^{-1}) having a higher value compared to the second season (10.86 kg ha^{-1} mm^{-1}) and the third season (7.92 kg ha^{-1} mm^{-1}) (Table 3). The high WUEp observed in the LR 2021 season coincided with the high biomass per plant (2.29 kg) recorded in the season. The WUEp under 100 % FC (4.75 kg ha^{-1} mm^{-1}) was 51 % and 75 % lower than in 60 % FC (9.74 kg ha^{-1} mm^{-1}) and 30 % FC (19.40 kg ha^{-1} mm^{-1}) respectively, with a trend of 30 % FC > 60 % FC > 100 % FC. The planting density did not influence the water use efficiency (*P = 0.390*) and the 1 m × 0.5 m planting density recorded the highest water use efficiency (12.16 kg ha^{-1} mm^{-1}) with the 0.5 m × 0.5 m recording the lowest (10.65 kg ha^{-1} mm^{-1}). The high WUEp under 30 % FC was associated with high biomass (1.97 kg) and low water use (2269.41 mm) under limited water conditions (30 % FC) (Table 3). Additionally, the growing seasons were significantly influenced by the planting density (*P = 0.005*) and watering regime (*P = 0.018*) (Table 3).

Table 3. Total Biomass, Corm Yield, Water Use, and Water Use Efficiency of taro under varying watering regimes and planting density for the LR 2021, SR 2021/2022, and LR 2022 planting seasons.

Season	**Total Biomass plant^{-1} (kg)**	**Yield (t ha $^{-1}$)**	**Water Use (mm)**	**WUEp (kg ha^{-1} mm^{-1})**
LR 2021	2.29^{c}	7.76^{a}	4874.35^{b}	15.11^{c}
SR 2021/2022	1.90^{b}	18.29^{b}	5097.43^{c}	10.86^{b}
LR 2022	1.26^{a}	10.59^{a}	4837.40^{a}	7.92^{a}
Watering Regime				
100 % FC	1.66	12.09	8269.95^{c}	4.75^{a}
60 % FC	1.83	12.76	4269.82^{b}	9.74^{a}
30 % FC	1.97	11.79	2269.41^{a}	19.40^{b}
Planting Density				
1 m × 1 m	2.12^{b}	5.56^{a}	2678.30^{a}	11.08
1 m × 0.5 m	1.8^{ab}	10.95^{b}	4484.78^{b}	12.16
0.5 m × 0.5 m	1.53^{a}	20.14^{c}	7646.09^{c}	10.65
Significant Levels				
Season	< 0.001	< 0.001	< 0.001	< 0.001
WR	0.742	0.929	< 0.001	0.003
PD	0.007	< 0.001	< 0.001	0.390
WR × PD	0.140	0.396	< 0.001	0.101
Season × WR	0.753	0.643	0.687	0.018
Season × PD	0.012	0.002	0.985	0.005
Season × WR × PD	0.726	0.337	0.834	0.179

Where, FC = Field Capacity, PD = Planting Density, WR = Watering Regime, Different letters within columns indicate significant differences at a 5% probability level

DISCUSSION

The 100 % FC watering regime had the least biomass, indicating that high water availability reduced biomass size, contradicting a study by Mabhaudhi *et al.* (2013) working on *Eddoe* and *Dasheen* taro cultivars in South Africa, who found that high moisture availability favoured biomass production. The 0.5m × 0.5m planting density (40000 plants ha^{-1}) had the lowest biomass and this can be attributed to competition for light, moisture, and nutrients at closer spacing. The corm yield was higher in the SR 2021/2022 season which was characterized by lower rainfall than the LR 2021 and LR 2022 season. This means that on a seasonal basis, lower rainfall amounts, and hence lower moisture availability favoured corm yield. The highest crop yield was obtained at the planting density of 0.5 m × 0.5 m (40,000 plants ha $^{-1}$) because a high number of plants per area increases photosynthesis while ensuring sufficient ground cover (Scheffer *et al.*, 2005; Tumuhimbise *et al.*, 2009; Youssef, 2010; Boampong *et al.*, 2020). The yields observed in this study were comparable to or higher than the averages for East Africa, Africa, and the world, which are 1 t ha $^{-1}$, 5.6 t ha $^{-1}$, and 6.6 t ha $^{-1}$, respectively (Serem *et al.*, 2008; Palapala and Akwee, 2016).

The low watering regime (30 % FC) and the low (1 m × 1 m) planting density had the lowest water use and in turn the lowest yield. This means that the reduction in water use (water applied) reduced the corm yield, similar to a study by Mabhaudhi *et al*. (2013). The seasons played a significant role in the determination of WUEp (Table 3), where reductions in rainfall reduced the WUE, with rainfall seasonal averages of 99.9mm (LR 2021), 88.4 mm (SR 2021/2022), and 86.5 mm (SR 2022) (Figure 2). The increase in WUEp with limited water availability (30 % FC) is associated with an increase in biomass and a decrease in water use (Table 3) due to the lower amount of irrigation applied. This was similarly reported by Mabhaudhi *et al.* (2013) working with South African *Dasheen* and *Eddoe* taro landraces planted under a rainshelter and Li *et al.* (2019) working with the Chinese taro variety in Brazil.

Similar studies have shown that the WUEp will be higher in water-limited conditions due to an increase in biomass or a decrease in the amount of irrigation water supplied to the crop (Pandey *et al.*, 2000; Shelembe, 2020). With the São Bento taro variety, Vieira *et al.* (2018) discovered a decrease in WUEp at higher watering regimes of 100 % and 125 % ETc. They also discovered that an increase in the depth of water application increased the WUEp. The trend of WUEp in this study was contradictory with the findings of Bussell and Bonin, (1998) working with drought-tolerant and traditional taro varieties who found WUEp to be generally higher at high watering-level treatments than at low water-level treatments. Uyeda *et al.* (2011) found that upland taro varieties use water more efficiently than varieties that are better suited to flooded conditions.

The low WUEp values under closer plant spacing (0.5 m × 0.5 m) signifies that with more plants per unit area, more water is used by the plants for growth and development and similarly lost through evapotranspiration, hence lower WUEp. However, due to the partitioning of the soil water evaporation and the transpiration of the canopy, Hatfield and Dold, (2019) concluded that plants in narrow rows would decrease the time the soil is not covered and, in theory, increase WUEp. Reducing plant row spacing could be a climate adaptation strategy for increasing WUEp in water-stressed environments or rain-fed environments with increasing variability in rainfall during the growing season (Hatfield and Dold, 2019).

CONCLUSION

The results demonstrate that different watering regimes and planting densities have various capacities to utilize the supplied water. Corm production was decreased and the total biomass per plant was increased due to the decrease in water use (water applied). The WUEp was considerably influenced by the watering regime, and the lowest watering regime resulted in both an increase in biomass and a decrease in water use because less irrigation water was used. The WUEp was greatly influenced by the seasons, and the seasonal WUEp increased as rainfall averages increased. Based on the findings of this study, the highest WUEp was obtained from planting at a medium density and a low watering regime. To achieve the highest yield per unit of water consumed, a watering regime of 30 % FC and a planting density of 1 m × 0.5 m (20,000 plants ha^{-1}) is recommended.

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Data Availability. The data is available with the first author – Joyce Wambui Njuguna joycenjuguna20@gmail.com upon reasonable request.

Author contribution statement (CRediT)
J.W. Njuguna - Conceptualization, formal analysis, methodology, visualization, software, writing – original draft, review and editing; **A.N. Karuma** - Conceptualization, project administration, funding acquisition, supervision, validation, review and editing; **P. Gicheru** - Conceptualization, project administration, supervision, validation, review and editing.

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