A COMPARATIVE WATER FOOTPRINT ANALYSIS OF ALTERNATE WETTING AND DRYING VS. CONVENTIONAL FLOODING IN RICE CULTIVATION

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https://doi.org/10.35410/IJAEB.2025.5985

ABSTRACT
Water scarcity poses a major threat to rice production, limiting irrigation expansion. To address this, an experiment was conducted at the Hembeti-Dihombo irrigation scheme in Tanzania to compare alternate wetting and drying (AWD) with continuous flooding (CF) in reducing the water footprint (WF) while maximising yield. The study used the SARO Malolo rice variety over two growing seasons (July–September and September–November 2023), with a randomised complete block design and three replications for each treatment forming 6 experimental plots. Each plot measured 1 m^2 and was separated by a 1 m buffer zone for lateral water movement prevention. The plant spacing was set at 400 cm2, accommodating 25 plants per square meter. Several growth parameters (plant height, canopy cover, the numbers of tillers, productive tillers, panicles and grains) and water usage were monitored with data collected on a daily and weekly basis. Results showed that AWD had a significantly lower average consumptive WF (0.1887 m^3/kg) than CF (0.3457 m^3/kg), achieving a 65.8% water savings without compromising yield. Statistical analysis confirmed the significance ($p < 0.05$) of the difference. The findings suggest that AWD is a more efficient irrigation method and should be promoted through policy support to improve water use efficiency in rice farming.

Keywords: Water Scarcity; Water Consumption; Water Application; Rice Yield, Irrigation Methods, Water Footprint.

1. INTRODUCTION
The global challenges of climate change and rapid population growth have had a significant impact on the availability of agricultural water, particularly in regions with semiarid and arid climates (Haris et al., 2023; Sharafi, Nahvinia and Salehi, 2024). Since water security and food security are closely interdependent, irrigated agriculture plays a central role in sustaining both (Chaudhary et al., 2023). To address the pressing need for water conservation and sustainable water management, numerous studies have been conducted to improve water use efficiency and crop yields in irrigated systems. Water footprint (WFP) analysis has emerged as one of the critical frameworks for evaluating the environmental impacts of agricultural production (Hoekstra et al., 2012). The WFP encompasses both direct and indirect water usage, capturing the total volume of freshwater consumed over a product's entire life cycle. It consists of green, blue, and gray water (Mekonen, Moges and Gelagl, 2022). Green WFP refers to the portion of rainwater retained by crops rather than becoming runoff, while blue WFP represents water extracted from sources such as rivers, reservoirs, and groundwater. Gray WFP denotes the

volume of freshwater needed to dilute pollutants to meet specific water-quality standards. Numerous studies have examined the WFP in agriculture across different crops and regions focusing primarily on lowering global freshwater consumption (Hoekstra and Chapagain, 2007; Lovarelli, Bacenetti and Fiala, 2016). In the context of rice farming, water footprint encompasses both rainfall (green water) and irrigation (blue water) consumption (Biswas, Mailapalli and Raghuwanshi, 2021; Chapagain and Orr, 2009). Rice cultivation is particularly relevant in global water management discussions, as rice fields constitute a substantial portion of irrigated agricultural land worldwide (Mekonnen and Hoekstra, 2014). When water use intensifies in insufficiently irrigated systems, reallocating resources can significantly minimize waste and raise yields by up to 30% (Caputo et al., 2021; Horton et al., 2021; Pfister et al., 2011). Consequently, reducing water consumption within this economic sector is vital for mitigating water scarcity (Chukalla, Krol and Hoekstra, 2015).

Over the past century, global freshwater withdrawal has increased more than sevenfold, primarily driven by population growth, urbanization, and changing dietary patterns (Mohapatra et al., 2019; Wada et al., 2010). This upward trend is expected to persist in the coming decades, especially in developing countries where food demand is escalating rapidly (Rockström et al., 2009). Rice, as the principal staple food for over half of the world's population, plays a significant role in this context (Han et al., 2021; Bouman et al., 2007). Recent projections indicate that the global demand for rice may reach 533 million tonnes by 2030 (Han et al., 2021), highlighting the necessity for further research aimed at enhancing rice yield while reducing water consumption. The urgency of this issue is exacerbated by climate change projections, which suggest increasing water scarcity in numerous regions, potentially constraining agricultural production and threatening food security (Hatfield & Walthall, 2015).

Tanzania, encompassing an area of 947,303 km², exemplifies the challenges of reconciling agricultural production with limited water resources in a developing country context. The nation accounts for 9% of Africa's total rice production—2.6 million tonnes out of the continent's overall 30.8 million tonnes (Materu et al., 2018). Tanzania's agricultural sector consumes 89% of its total water withdrawals, significantly exceeding the global average of 70% (World Bank, 2017). Despite these high withdrawal rates, water scarcity persists, creating a production–consumption gap and fostering reliance on imported rice (Materu et al., 2018). Similar challenges are encountered by other countries across sub-Saharan Africa, where growing populations and limited irrigation infrastructure exacerbate existing water constraints (Savva and Frenken, 2002).

Rice farming methods traditionally necessitate between 1,000 and 2,000 mm of field water per hectare which is two to three times more than other cereal crops (Materu et al., 2018; Tuong & Bouman, 2003). Notably, significant water losses occur through evapotranspiration, surface runoff, seepage, and deep percolation (Materu et al., 2018). These inefficiencies underscore the importance of implementing strategies to reduce rice's water footprint. One promising approach involves optimizing irrigation management through techniques such as alternate wetting and drying (AWD), which can substantially decrease water inputs without compromising yields (Tripathi et al., 2018; Lampayan et al., 2015). Over the past two decades, multiple innovations—including improved irrigation scheduling, better field leveling, and innovative seed varieties—have been developed to address water shortages and enhance water-use efficiency (Punyawansiri et al., 2020; Bouman & Tuong, 2001). Alternate wetting and drying (AWD) techniques have been implemented in several Asian countries, often resulting in considerable reductions in

ISSN: 2456-8643

irrigation requirements without sacrificing yields (Lampayan et al., 2015; Tripathi et al., 2018). However, despite promising global findings, there is a relative scarcity of systematic studies assessing the effectiveness of AWD and similar techniques in African settings (Africa Rice Center, 2011; Punyawansiri et al., 2020). This knowledge gap is especially evident in Tanzania, where climatic, infrastructural, and socioeconomic conditions differ significantly from leading rice-producing regions in Asia (Materu et al., 2018; Niang et al., 2014).

The global rice demand is expected to reach 533 million tonnes by 2030 due to increasing demands (Han et al., 2021). This study seeks to evaluate and compare the water footprints of rice cultivation using two irrigation methods: conventional continuous flooding and alternate wetting and drying (AWD). The conventional method involves maintaining a continuously flooded field, while AWD provides for periodic non-flooded intervals, potentially lowering overall water use and related losses. By examining water footprint metrics under these different systems, this study offers vital insights for policymakers, farmers, and environmental stakeholders, contributing to improved water efficiency, increased crop productivity, and reduced environmental impacts of rice farming in Tanzania and other sub-Saharan African regions. The results from this comparison will provide valuable insights for agricultural policymakers, farmers, and environmental stakeholders, ultimately contributing to strategies that optimize water use, enhance crop productivity, and mitigate the environmental impacts associated with rice cultivation.

1.1 Methodology

1.1.1 Description of the Study area

The study was carried out at the Hembeti-Dihombo traditional irrigation scheme in the Mvomero district of Tanzania's Morogoro region. Established in 2001 by local farmers inspired by the success of the neighboring Mkindo irrigation scheme, this site is located in Hembeti ward and encompasses the villages of Hembeti and Dihombo. Geographically, it lies between latitudes 6°16'6.8"S and 6°16'51.95"S and longitudes 37°31'29.7"E and 37°32'4.19"E, adjacent to the Turiani–Morogoro road and about 35 km from the Mvomero district headquarters (Figure 1). The perennial Dizingwi River, which has a minimum discharge of around 3 m^3/s, serves as the primary water source for irrigation.

Although the Hembeti-Dihombo scheme encompasses 2,000 hectares of potential irrigable land, only 223 hectares are currently under irrigation. Plans are underway to fully develop its water control structures and eventually irrigate more than 1,000 hectares (Mvomero DC, 2021). The district's predominant soil type is sandy loam, and the landscape is mostly grassland. Rainfall follows a bimodal pattern, with the long rains occurring between March and May and the short rains between October and December (Figure 2). Average temperatures range from a maximum of 29.7°C in December to a minimum of 24.4°C in July, while relative humidity stands at about 69.7%. Major crops in the region include rice, maize, sorghum, and sunflower.

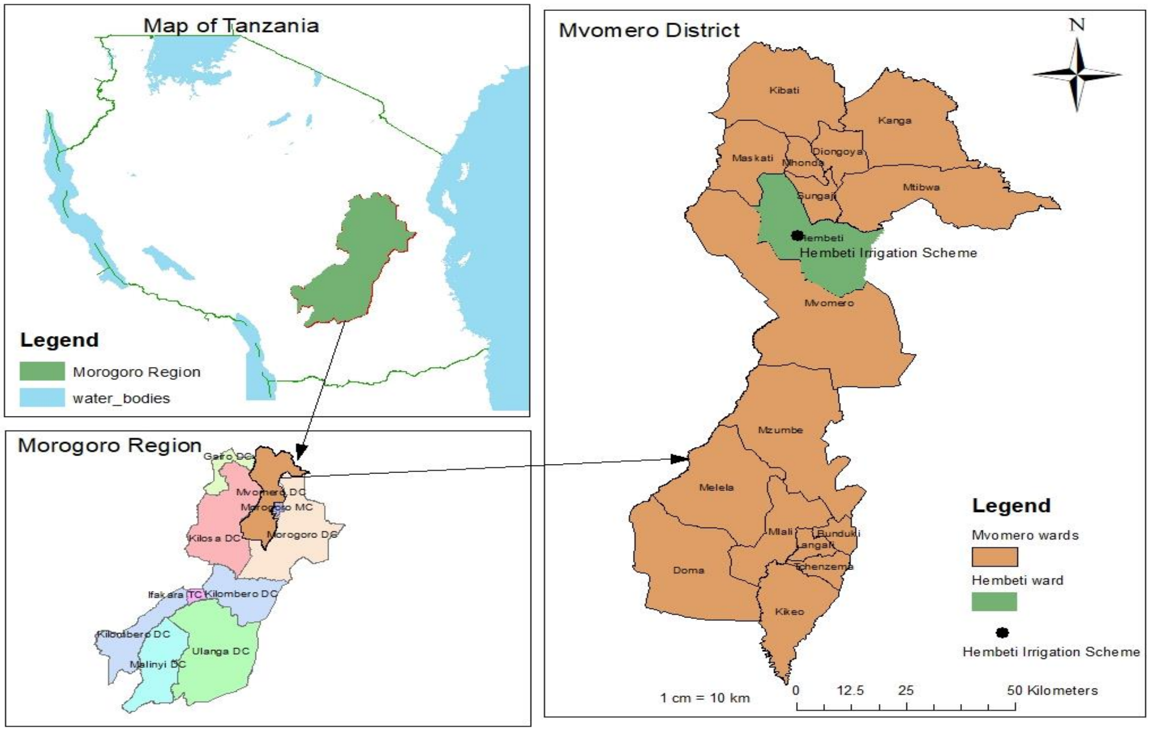


Figure 1: Map of Morogoro region showing the Hembeti-Dihombo irrigation scheme

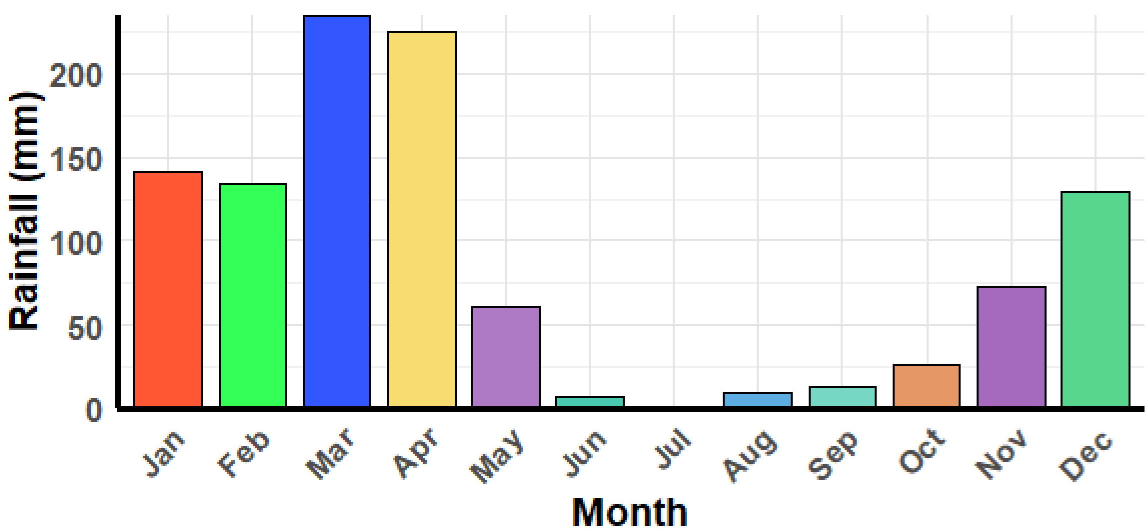


Figure 2: Mean monthly rainfall for the study area

1.1.2 Experimental design

A randomized complete block design was utilized for setting up and developing the field experiment at the Hembeti-Dihombo irrigation scheme. The size of each plot was set to 1 m² (1 m x 1 m), and the two treatments were assigned to the plots randomly. The plots had a 1 m buffer zone separating them to prevent lateral movement of water between the plots as shown in Figure 3. The same variety of rice with a 90-day growing span (SARO malolo, a cross of YY and Super) was transplanted at an age of 17 days, in all plots at the same grid spacing of 20 cm x 20 cm resulting in 25 rice plants per square meter (Table 1). Crop height, canopy cover, number of tillers per hill, number of productive tillers per hill, number of panicles per hill, number of grains per panicle, and yield were among the variables that were tracked. Additionally, the quantity of water applied and consumed was noted.

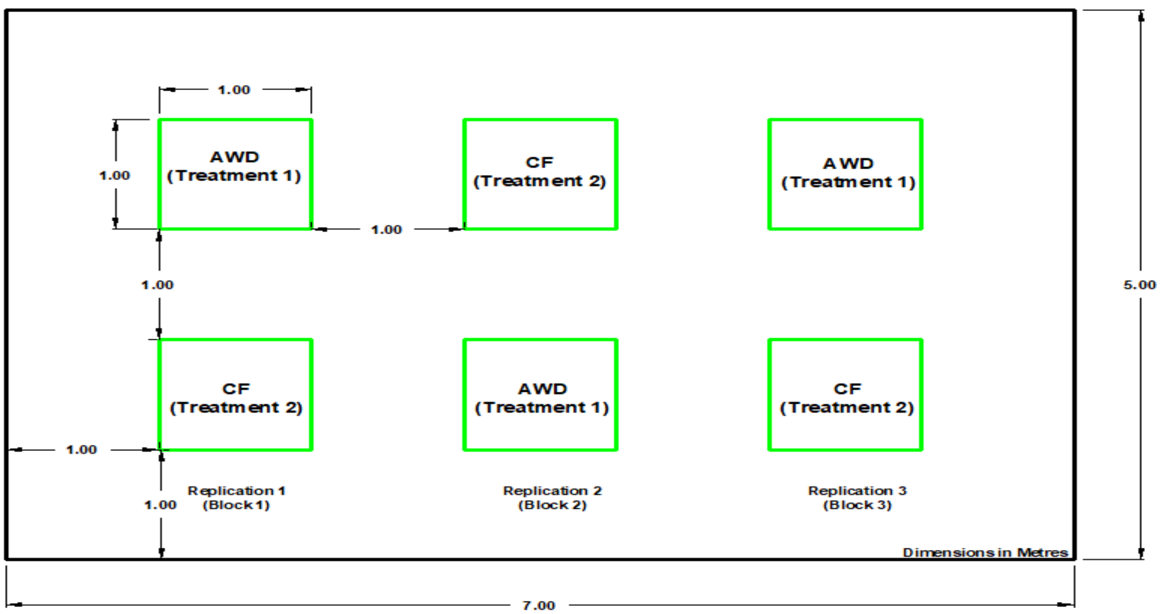


Figure 3: Layout plan of the experimental plots

Table 1: Treatment details on the experimental plots

Treatment	Water application regime	Transplanting age (days)	Seedling per hill	Spacing (cm)
T1	Alternate wetting and drying	17	1	20 x 20
T2	Continuous flooding	17	1	20 x 20

ISSN: 2456-8643

1.1.3 Field establishment and management

The experiment was conducted over two seasons within a span of five months. The two seasons overlapped by one month: the first season ran from July to September 2023, while the second season took place from September to November 2023, following the scheme's farming schedule. The sunken experimental plots were established in two areas of the same field, ensuring that both areas had identical physical and chemical soil properties. Two raised seedbeds were prepared for nursery establishment: one in June for season 1 and the other in August for season 2. Rice seeds were broadcast on each bed and left for 17 days to germinate and develop into seedlings before transplanting. One seedling per hill (17 days old) was transplanted in a square pattern of 20 cm by 20 cm on 1m2 sunken experimental plots.

Fertilizer and pesticide applications were carried out to ensure proper growth. DAP was applied during transplanting, and UREA (46% N) was applied as split application on the 14th and 50th days after transplanting (DAT) both at a rate of 100 kg/ha (Mbaga, 2015). Additionally, lambda-cyhalothrin 50 g/L, an insecticide, was applied at a rate of 5 mL per 2.5 litres of water every week. The irrigation water ponding depth for the controlled flooding (CF) system was maintained at 30 mm from transplanting until crop maturity (Nyamai et al., 2012). Excess water was drained through channels to prevent overflow. In the AWD system, water was applied as per designed irrigation schedule basing on crop water requirements, field application efficiency, total available water and the minimum allowable depletion of soil moisture.

1.1.4 Data collection procedure

1.1.4.1 Soil sampling and analysis

Soil data were collected following analysis by the TARI Mlingano Central Soils Laboratory. A total of 12 soil samples were taken from the Hembeti irrigation scheme, consisting of 6 core samples and 6 composite soil samples. These samples were analysed for soil water retention characteristics (pF determination), bulk density, and standard fertility assessment for the composite samples.

1.1.4.2 Climate data

The 20-year climate data (2003 – 2022) for the study area (Table 2) was collected from the nearest meteorological station, TARI Ilonga, to estimate Crop Evapotranspiration (ETc) using the CLIMWAT/CROPWAT model. The collected data included maximum and minimum temperatures, humidity, wind speed, sunshine duration, and rainfall, all recorded on a monthly basis.

Table 2: Average monthly weather data (20-year period) for study area

Weather variable	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Max T. °C	29.1	28.9	28.2	26.5	25.6	24.9	24.4	25.3	26.8	28.3	29.4	29.7
Min T. °C	19.5	19.3	19.4	18.9	16.8	14.6	13.8	14.4	15.4	17.1	18.7	19.5

Wind (m/s)	1.2	1.3	1.5	2.1	2.2	2.3	2.4	2.5	2.6	2.6	2.2	1.6
R.H (%)	72.2	73.0	78.3	82.4	76.4	67.7	63.8	63.6	61.7	62.9	66.4	68.4
Rain (mm)	140.7	133.9	234.6	225.1	60.9	6.8	1.3	9.2	12.5	26.3	72.6	129.5
Sunshine (hours)	5.6	6.5	7.0	5.9	6.4	7.0	7.0	6.7	7.1	8.1	8.2	8.0

1.1.4.3 Water application

a) For AWD, the amount of water applied was determined by considering the crop water requirements, field application efficiency, minimum allowable soil moisture depletion and total available water (T.A.W). The crop water requirement for rice was estimated using the CLIMWAT/CROPWAT model, which incorporated climate, soil, and crop data to calculate the net depth of water application. The field application efficiency for surface irrigation was set at 60%, and the minimum allowable moisture depletion was 50% and T.A.W ranging from 119 mm water/m soil to 125 mm water/m soil as shown in Table 3. The gross irrigation application depth was calculated by dividing net depth of water application (mm/day) by the field application efficiency.

The gross volume of water applied to a plot (plot's length x plot's width x gross depth) was calculated by considering the flow discharge (m^3/s) and the time (s) taken. Flow discharge is a product of current flow velocity (m/s) and the flume's cross-sectional area (m^2). The current flow velocity was measured using the float method, which involved placing a small piece of leaf on the flowing water in the channel, and the distance it travelled over time was recorded. The current flow velocity was then calculated as the ratio of distance travelled (m) to time (s).

$$Q \times t = d \times A \qquad (1)$$

Where Q is the flow rate (discharge),

t is the set time or total time of irrigation,

d is the depth of water applied,

A is the area irrigated.

Known depth d of water applied on known area A of the plot was measured by allowing water to flow with a known discharge Q for time t.

Flow rate (discharge) was calculated by the formula;

$$Q = \text{flow velocity } (V) \times \text{water flume area } (Af) \qquad (2)$$

b) The ideal irrigation schedule was established using a tensiometer. The experimental site's sandy loam soil had a moisture content ranging from 22.5% to 25.3% at field capacity (FC) which was equivalent to about 11 centibars, and moisture content from 10.0% to 13.4% at wilting point (PWP) (Table 3). Tensiometer readings between 70 and 80 centibars would indicate excessive drying, thus irrigation was started when the reading hit 40 to 50 centibars.

c) For CF, water was applied to maintain a ponding depth of 30 mm from transplanting until crop maturity (Nyamai et al.,2012), i.e., amount of water applied through CF was measured by refilling the plot with respect to depth and area of the plot.

Table 3: Soil Moisture content (%) for the study area

Soil sample ID.	θ_{FC} (Vol.%)	θ_{PWP} (Vol. %)	T.A.W (mm water/m soil)
A1	23.7	11.3	124
A2	22.5	10.0	125
A3	24.6	12.7	119
C1	25.1	12.9	122
C2	22.8	10.4	124
C3	25.3	13.4	119

θ_{FC} =Soil moisture at FC; θ_{PWP} =Soil moisture at PWP=Permanent Wilting Point; T.A.W=10 (θFC- θPWP) [mm (water)/m(soil depth)]

The percentage water saved was calculated using the formula:

$$\frac{\text{Water applied (CF Plot)} - \text{Water applied (AWD Plot}}{\text{Water applied (CF Plot)}} X\ 100\% \quad (3)$$

(Chapagain and Riseman, 2010)

1.1.4.4 Crop height

The height of rice plants was measured using a ruler or measuring tape, from ground level to the tip of the tallest leaf (FAO, 2004).

1.1.4.5 Crop canopy cover

The percentage of ground covered by the vertical projection of the outermost perimeter of the natural spread of rice plants (FAO, 2020) was measured biweekly using a mobile app called Canopy Cover Free. This app features sliders for adjusting parameters to ensure accurate canopy identification, such as the leaf green-red ratio, leaf green-blue ratio, and G minimum (Yu et al., 2020). It also provides the latitude and longitude of the area.

1.1.4.6 Tillers per hill

During the growing season, the number of tillers on each hill was recorded for both treatments. Data were collected from the experimental plots, where a random sample of five hills from each plot was selected for observation and marked with a slender stick inserted into the soil during the early stages of plant development. To gather data for the study, tillers were manually counted weekly throughout the growing season. At the crop maturity stage, the number of productive tillers per hill was also counted (Reuben et al., 2016).

1.1.4.7 Panicles per hill

At crop maturity, the number of panicles per hill was counted using the five randomly selected hills. The total number of panicles from each hill was summed and averaged to estimate the average number of panicles per hill.

1.1.4.8 Grains per panicle

One of the factors influencing rice yield is the number of grains per panicle. As the quantity of grains per panicle increases, the yield of rice also rises. To assess this, the number of grains per panicle at crop maturity was recorded from the five randomly selected hills. The grain count from each panicle was totalled, and the results were averaged before being entered onto a recording sheet for analysis (Reuben et al., 2016).

1.1.4.9 Crop yield

During harvesting, rice panicles were cut from the tillers, and the rice seeds were separated from the straws. The seeds were weighed using a measuring balance and recorded on a data recording sheet as fresh weight. The fresh weight grains were then sun-dried for three consecutive days. After this period, the dry grains were weighed, and the data recorded for analysis. Rice grain yield estimation was conducted at the end of each cropping season using the following formula:

$$\text{Yield in 1 hectare area} = \text{Yield of 1 plant x Number of plants or productive tillers} \quad (4)$$

Where $$\text{Yield of 1 plant} = \text{Grain weight x Number of grains per plant} \quad (5)$$

$$\text{Number of plants} = \frac{1 \text{ ha area in m}^2}{\text{plant spacing area in m}^2} \quad (6)$$

1.1.5 Water footprint of rice

The blue and green water footprints were calculated based on the water consumption from irrigation and rainfall, in addition to yield as per equations 7 and 8:

$$WF_{green/blue} = \frac{CWR_{green\ or\ blue}}{Y} \quad (7)$$

Where $CWR_{green/blue}$ - green/blue crop water requirement
Y - grain yield

$WF_{green/blue}$ - green/blue water footprint

$$\text{Consumptive water footprint of rice (CWFrice)} = \text{WFblue} + \text{WFgreen} \quad (8)$$

1.1.6 Data analysis

An analysis of variance (ANOVA) was conducted using R version 4.3.2 to assess the variations between rice crops irrigated with AWD and CF treatments. The variables examined included plant height, crop canopy cover, total number of tillers, productive tillers, and water application. Mean separation was performed using Tukey's Honestly Significant Difference (HSD) test at the 0.05 significance level. The results for the variables were illustrated using bar graphs to analyse trends and differences.

1.2 Results and Discussion

1.2.1 Physical and chemical properties of soil at the study area

1.2.1.1 Soil physical properties

The bulk density values for all the samples range from 1.04 to 1.21 g/cc, which is generally acceptable as it indicates good porosity and aeration, which are beneficial for rice cultivation (Figure 4). Lower bulk density indicates a relatively loose soil structure, which allows rice roots to penetrate more easily. Variation in bulk density could be due to natural variations in soil properties, differences in land management practices, and environmental influences. The porosity percentages among the samples varied slightly from 39.2% to 43.2% (Figure 4). These values are reasonable for rice cultivation, as they suggest the presence of adequate pore spaces for air and water movement. The total available water on a volume basis varies from 11.9% to 12.5%, the corresponding T.A.W values in mm water/m soil range from 119 to 125. This suggests a moderate to high availability of water across all samples, though differences in porosity and bulk density slightly affect the amount of available water (Figure 4) that the soil can hold, which is crucial for rice plants during periods of limited rainfall. Overall, the soil analysis results indicated that the samples had reasonable characteristics for rice cultivation.

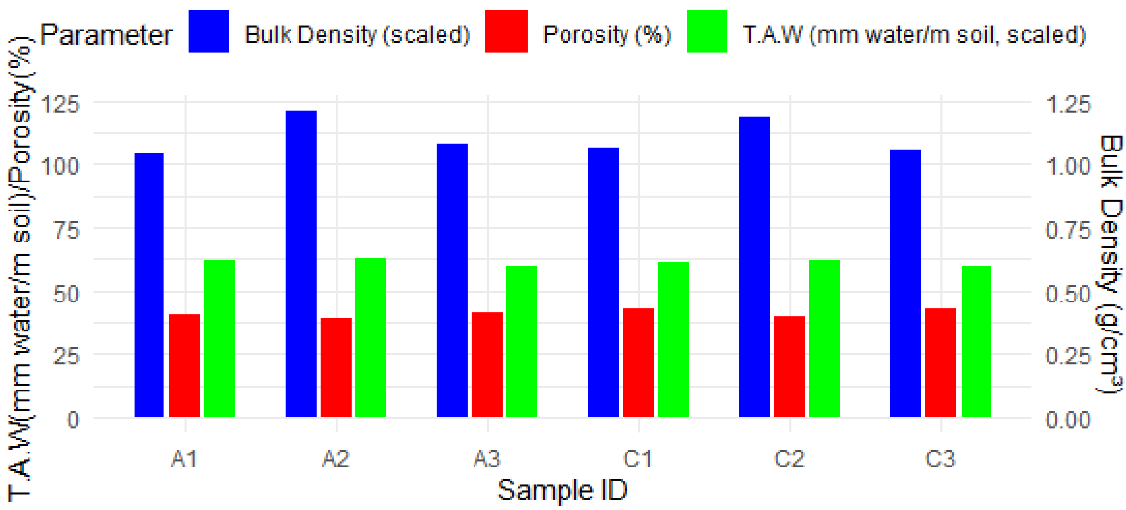


Figure 4: Bulk density, Porosity and Total available moisture/water for soil samples A1, A2, A3, C1, C2, C3.

Soil Texture

Rice grows well in soils with low salinity level, good water retention capacity such as those with a high percentage of clay or organic matter, are often better suited for rice production. The soil texture for all samples (A1, A2, A3, C1, C2, C3) taken from the experimental plots A1, A2, A3, C1, C2, and C3 respectively; had an average composition of 52.3% sand, 29.3% silt and 18% clay which falls under sandy loam soil texture which is acceptable for rice cultivation (Table 4).

1.2.1.2 Soil chemical properties

Soil pH

Rice prefers slightly acidic to neutral soils for optimal growth. The pH values in the samples ranged from 5.3 to 6.3 (Table 4). Msanya et al. (2001) and Landon (2014) reported that medium acidic soil has a pH ranging from 5.5 to 7.0 and Pawar et al. (2009) rated a soil pH of between 5.3 and 6.5 as moderately/slightly acidic and therefore suitable for rice cultivation.

Electrical Conductivity

Electrical conductivity (EC) serves as an indicator of soil salinity. Generally, lower EC values correspond to lower soil salinity, and vice versa (Che Othaman et al., 2020). High salinity can negatively impact rice growth. The EC values for all samples analysed were relatively low, ranging from 0.01 to 0.06 mS/cm (Table 4). This finding aligns with the laboratory manuals of Pawar et al. (2009) and Maral (2010), which indicate that an electrical conductivity range of 0 to 10 mS/cm is optimal for soil supporting rice cultivation.

Total Nitrogen and Organic Carbon

Organic Carbon (OC) is a measure of the organic matter content in the soil, while Total Nitrogen (TN) indicates the amount of nitrogen present. Nitrogen is essential for rice growth and is often supplied through the breakdown of organic matter. According to Table 4, sample A1 had the highest TN content at 0.12%, whereas sample C2 had the lowest at 0.02%. Msanya et al. (2001) and Landon (2014) categorized TN levels of less than 0.1% as very low. This low TN content may be attributed to nutrient leaching due to irrigation or uptake by plants. Therefore, it has been recommended to use nitrogen-rich fertilizers to enhance productivity (Gowele, 2021). Pawar et al. (2009) classified OC content greater than 1.0% as very high and less than 0.2% as very low. Samples analysed showed OC content ranging between 1.02% and 1.38%, which is favourable for rice production. Additionally, the residue from rice plants contributes significantly to OC levels, as this biomass is typically incorporated into the soil when preparing for the next planting season.

C:N Ratio

The Carbon-to-Nitrogen ratio (C:N) is a crucial factor influencing the decomposition rate of organic matter, as it represents the balance of carbon and nitrogen in the soil. A higher C:N ratio indicates a greater abundance of carbon-rich organic matter relative to nitrogen-rich compounds. According to Rajani (2019), the C:N ratio in arable (cultivated) soils typically ranges from 8:1 to 15:1. In the soil samples analysed, the C:N ratios ranged from 8:1 to 12:1 (Table 4), suggesting a smaller disparity between carbon and nitrogen quantities in the soil organic matter, which is conducive to plant growth.

Na, K, P-Bray1, Ca, Mg

These elements represent the soil's nutrient content. They are important for plant growth and play crucial roles in various biochemical processes in the soil. Adequate nutrient levels are necessary for rice growth. The nutrient levels in the samples appeared to be appropriate for rice cultivation, though slight variations were observed among the samples (Table 4). The Na levels in all samples (0.11-0.14 meq/100g) are low, which is generally positive for rice cultivation. Excessive sodium can lead to soil salinity issues, negatively affecting rice growth. According to Singh et al., (2019), Na levels under 1 meq/100g are considered safe for rice production, suggesting that Na concentrations in these samples are well within acceptable limits. Potassium levels range from 0.15 to 0.27 meq/100g across samples. The critical level of K for rice is around 0.2 meq/100g or higher in soils, which means that most of the samples meet or exceed this level. Only sample C3 is slightly lower but still within the manageable range. Adequate K is essential for proper growth, grain filling, and resistance to pests. P-Bray 1 values range from 6.8 to 9.6 mg/kg, which are appropriate for rice cultivation. Phosphorus is crucial for root development and early growth stages. According to Dobermann and Fairhurst (2000), P levels in rice paddies should ideally be between 5-10 mg/kg, aligning with the values in these samples. Calcium levels range between 0.35 to 0.76 meq/100g. Adequate Ca is necessary for cell wall integrity and proper root development. A Ca level above 0.3 meq/100g is generally considered sufficient for rice cultivation, meaning all the samples fall within or above the recommended range. Magnesium levels in the samples vary between 1.7 to 3.12 meq/100g, which is appropriate since Mg plays an important role in photosynthesis and enzyme activation. Fageria (2014) suggests that Mg levels above 0.2 meq/100g are needed for rice, so all samples have adequate Mg levels for optimal rice production.

Calcium-to-Magnesium Ratio (Ca/Mg)

The calcium-to-magnesium ratio in the soil is essential for maintaining proper soil structure and facilitating nutrient uptake by plants. This balance is vital for soil fertility. According to Maral (2010), calcium and magnesium are among the key parameters used for assessing soil efficiency. Specifically, calcium levels below 2.38 meq/100g (1.19 mmol/100g) are classified as very low, while magnesium levels between 2.68 and 8 meq/100g (1.34 - 4.0 mmol/100g) are considered medium. Table 4 indicates that the concentration of calcium ions in the samples ranged from 0.35 to 0.76 meq/100g, which is significantly lower than the magnesium ions concentration of between 1.7 and 3.12 meq/100g. This results in a calcium to magnesium ratio of 0.2:1. Consequently, the soil in the study area is identified as calcium deficient. A study conducted by Alva and Edwards (1996) found that calcium-deficient soils often result in poor root elongation, limiting the ability of plants to absorb water and nutrients effectively. It is therefore recommended to apply fertilizers rich in calcium to restore the ratio to at least 3:1 (Ca/Mg). However, there is very little research evidence to support any effect, either positive or negative, of the soil Ca/Mg ratio on crop production and yield. But since Mg works closely with Ca, it is important to have an appropriate ratio of both minerals in order for them to be effective. A good rule of thumb is a 2:1 Ca/Mg ratio (Magdoff, F., et al., 2009)

CEC

Cation Exchange Capacity (CEC) refers to the soil's capability to retain and supply cations (positively charged ions) such as potassium, calcium, and magnesium for plant uptake (Saha, 2022). Higher CEC values indicate better nutrient retention capacity. In this study, the CEC values for all samples ranged from 4.2 to 6.2 meq/100g. However, Saha (2022), in his revised paper on cation exchange capacity and base saturation, reported CEC values for sandy loam soil between 5 and 10 meq/100g. This suggests that the soil in the study area has good potential for retaining and supplying nutrients to rice plants (Table 4).

Base Saturation

The base saturation percentage indicates the proportion of exchangeable bases to the total CEC, representing the percentage of CEC occupied by base cations, including calcium, magnesium, potassium, and sodium (Horneck et al., 2019). The base saturation (BS) values for the samples ranged from 55% to 74% (Table 4), with corresponding soil pH levels between 5.3 and 6.3, indicating low acidity, which is favourable for rice production (NARO, 2010).

Table 4: Soil analysis results for six different samples at Hembeti-Dihombo irrigation scheme

SAMPLE ID.	SAND	SILT	CLAY	pH	pH	EC	TN	OC	C:N	Na	K	P-Bray 1	Ca	Mg	Ca/Mg	CEC	BS
↓	%	%	%	water	Kcl	mScm	%	%	↓	(meq/100g)	(meq/100g)	(mg/kg)	(meq/100g)	(meq/100g)	↓	(meq/100g)	%
A1	56	28	16	5.9	5.2	0.06	0.12	1.26	11	0.12	0.20	9.6	0.48	2.07	0.2	4.20	68
A2	40	32	28	5.6	4.8	0.03	0.11	1.02	9	0.13	0.26	7.8	0.66	3.12	0.2	5.60	74
A3	54	30	16	6.3	5.6	0.04	0.16	1.28	8	0.11	0.21	8.2	0.49	2.35	0.2	4.80	66
C1	56	32	12	6.1	5.3	0.04	0.14	1.08	8	0.14	0.22	9.4	0.76	2.94	0.3	6.20	65
C2	54	26	18	5.8	5.1	0.0	0.1	1.3	8	0.12	0.27	8.6	0.62	2.64	0.2	5.40	68

						2	8	8								
C3	54	28	18	5.3	4.4	0.01	0.11	1.36	12	0.12	0.15	6.8	0.35	1.70	0.2	4.20	55

1.2.2 Blue and green water consumption

The amounts of blue water used in Season 1 were 320 mm for the AWD method and 1,068 mm for CF method. In Season 2, the blue water applications were 308 mm for AWD and 1,007 mm for CF. Additionally, the amounts of green water (rainfall) received in Seasons 1 and 2 were 20 mm and 102 mm, respectively (Table 5) of which, 19.8 mm and 89.8 mm were considered effective rainfall, which refers to the amount stored in the soil's root zone available for plant uptake. The average water consumption for rice in both seasons was 281.8 mm for the AWD plots and 449.95 mm for the CF plots. There was a significance difference in the amount of water applied between the AWD and CF treatments at $p = 0.05$. The sandy loam texture may have contributed to excessive water depletion through infiltration and percolation, necessitating frequent water refills to maintain a ponding depth of 30 mm under the CF plots throughout the cropping season. The intermittent water application likely explains the lower water usage in the plots with the AWD treatment, which achieved a 65.8% reduction in water use compared to the CF treatment. Most studies have reported water savings of between 20% and 70% with the AWD technique, without any significant change in yield (Majeed et al., 2017).

Table 5: Blue and green water consumption for AWD and CF treated plots

Treatment	Water applied (mm)		Water consumed (mm)	
	Blue water	Green water	Blue water	Green Water
AWD-S1	320	20	210	19.8
CF-S1	1068	20	424	20
AWD-S2	308	102	244	89.8
CF-S2	1007	102	354	101.9

S1=Season 1, S2=Season 2

1.2.3 Crop height versus water application

There was no significant difference ($p = 0.05$) in plant heights between the AWD and CF treatments for both seasons and across replicates. Plant heights in both treatments increased proportionally with the amount of water applied up to the flowering stage; however, no further height increase was observed with additional water applications until the maturity stage. The average maximum heights and corresponding amounts of water applied were 125.6 cm and 375 mm for AWD, and 126.2 cm and 1,091 mm for CF (Figures 5, 6). Phoeurn (2024) reported that, the average plant heights in field 1 were 91 cm under AWD and 93 cm under CF (no significant difference at P < 0.01), while in field 2, the plant heights were 102 cm under AWD and 104 cm under CF, respectively (no significant difference at P < 0.01). The slight variation in heights may be attributed to the specific rice variety used in the experiment, which may possess genetic traits that enhance its resilience to water stress, flooding stress, and poor soil aeration, thereby enabling it to maintain growth under both AWD and CF conditions (Panda et al., 2021; Panda and Barik, 2020).

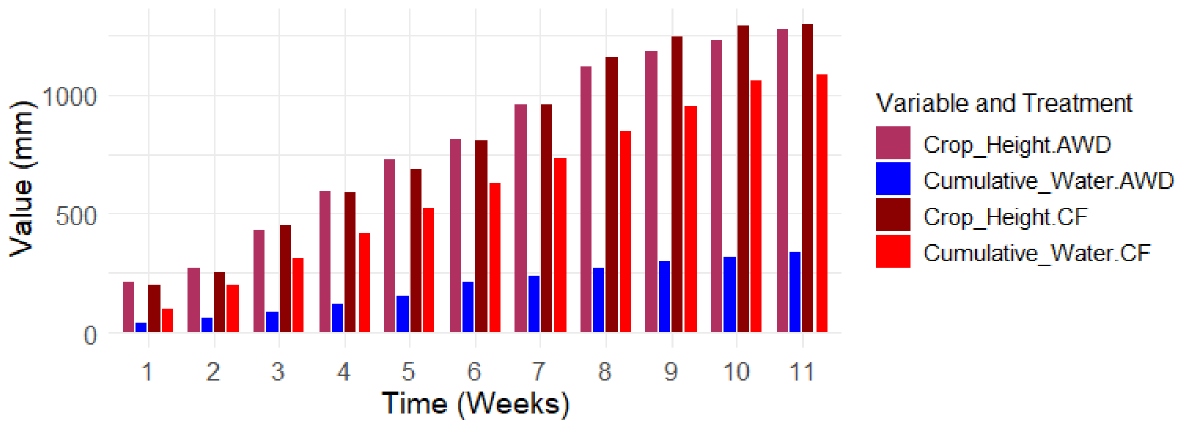
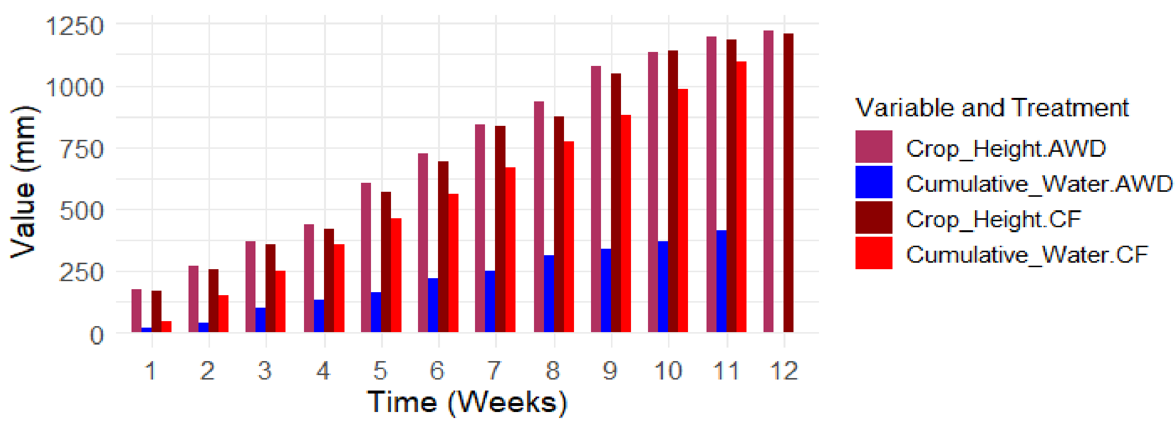


Figure 5: Rice plant height with cumulative water application for AWD and CF plot – Season 1



1.2.4 Total number of tillers per hill vs productive tillers

The results indicate an increase in the number of tillers that correlated with the cumulative amount of water applied. Tillering continued until maturity, resulting in the presence of unproductive tillers at the time of harvest. For both seasons, the average number of tillers per hill was 21 for the AWD treatment (with 375 mm of water applied) and 21 for the CF treatment (with 1,091 mm of water applied) (Tables 6, 7). Furthermore, the average number of productive tillers per hill was 10 for the AWD treatment and 9 for the CF treatment across both seasons, showing only slight variation between the two treatments (Table 8). The findings indicate no significant difference ($p > 0.05$) in the quantity of productive tillers per rice hill between the AWD and CF treatments in both seasons. These findings are consistent with those of Reuben et al. (2016) though the number of unproductive tillers was notably lower in their study.

Table 6: Tillering of rice plant against cumulative amount of water applied – Season 1

Number of Weeks after transplanting	Average number of tillers per hill (AWD)	Cumulative water applied (mm) - AWD	Average number of tillers per hill (CF)	Cumulative water applied (mm) - CF
1	2	40.00	1	97.00
2	2	60.00	1	201.00
3	4	90.00	4	309.67
4	8	120.00	7	418.33
5	11	150.00	11	523.00
6	14	210.00	14	626.33
7	17	240.00	15	735.00
8	19	270.00	17	844.67
9	20	300.00	18	951.00
10	21	320.00	19	1057.00
11	22	340.00	21	1088.00
12	22	**-**	21	**-**

Table 7: Tillering of rice plant against cumulative amount of water applied – Season 2

Number of Week after transplanting	Average no. of tillers (AWD)	Cumulative water applied (mm) - AWD	Average no. of tillers (CF)	Cumulative water applied (mm) - CF
1	2	20.00	2	44.67
2	3	40.00	3	151.34
3	3	100.00	3	252.67
4	5	130.00	5	358.34
5	6	160.00	5	460.34

6	9	220.00	9	564.00
7	13	250.00	12	668.67
8	15	310.00	16	774.34
9	17	340.00	18	879.67
10	17	370.00	18	986.00
11	19	410.00	20	1095.00
12	19	0.00	20	0.00

Table 8: Number of tillers Vs productive tillers of rice plant for AWD and CF treated plots

	(AWD)-S1	**(CF)-S1**	**(AWD)-S2**	**(CF)-S2**
Average number of tillers per hill	22	21	19	20
Average number of productive tillers per hill	10	9	10	8

S1=Season 1, S2=Season 2

1.2.5 Crop canopy cover in relation to water application

The crop canopy cover increased proportionally with cumulative water application until a point was reached where no further increase in canopy percentage occurred. As water application increased, plant height also rose, enhancing both the upward and sideways growth of leaves, which contributed to a higher percentage of canopy cover (Yu et al., 2020). Additionally, tillering played a role in augmenting canopy cover. However, the research conducted by Phoeurn (2024) demonstrated that CC is not affected by water regime; rather, it is greatly impacted by the soil type and rice variety. For the four rice varieties (CAR15, OM, SK, and SP) transplanted in sandy loam and sandy clay loam soils with a uniform hill spacing of 20 cm by 20 cm, the maximum canopy cover (CC) in both AWD and CF regimes was 60%, 47%, 50%, and 52%, respectively.

The results indicated no significant difference ($p > 0.05$) in the mean canopy cover between the treatments or among replicates. The average maximum canopy cover for the AWD and CF treatments in both seasons was 94.9% and 94.6%, respectively. These corresponded with maximum water applications of 375 mm for AWD and 1,091.5 mm for CF. Notably, the maximum canopy cover reached 97% for AWD and 95.27% for CF in season 1, while in season 2, the values were 92.8% for AWD and 93.9% for CF (Tables 9, 10; Figure 7) and according to Suzuki et al., (2013), increases in canopy coverage reduce surface water evaporation, which in turn improves WUE, i.e., higher amount of water applied is consumed and less is lost as evaporation is largely dependent on solar radiation.

ISSN: 2456-8643

Table 9: Rice canopy cover with cumulative water applied in AWD and CF – Season 1

Number of weeks after transplanting	Average canopy cover (%) - AWD	Cumulative water applied (cm) - AWD	Average canopy cover (%) - CF	Cumulative water applied (cm) - CF
2	14.37	6.00	14.13	20.10
4	58.93	12.00	54.17	41.80
6	71.97	21.00	73.23	62.60
8	89.17	27.00	88.33	84.40
10	96.73	32.00	94.27	105.70
12	97.00	-	95.27	-

Table 10: Rice canopy cover with cumulative water applied in AWD and CF – Season 2

Number of weeks after transplanting	Average canopy cover - AWD (%)	Cumulative water applied (cm) - AWD	Average canopy cover - CF (%)	Cumulative water applied (cm) - CF
2	5.47	4.00	4.63	15.13
4	16.33	13.00	17.20	35.83
6	38.43	22.00	35.03	56.40
8	71.23	31.00	73.17	77.43
10	88.63	37.00	90.90	98.60
12	92.80	-	93.93	-

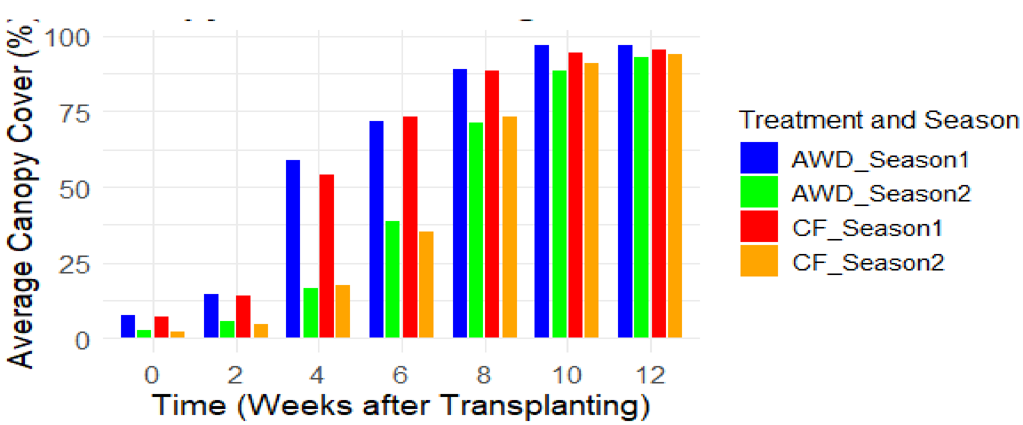


Figure 7: Rice canopy cover percentage for AWD and CF treated plots

1.2.6 Number of panicles per hill

The average number of panicles per hill was 10 for plots under AWD and 9 for those under CF (Table 11). The results indicate that the difference in the number of panicles between the two treatments was not statistically significant at the 0.05 level, suggesting only a slight variation in panicle count. Reuben et al., (2016) obtained an estimated 20 number of panicles under AWD which is twice the count for this research. This may be attributed to the rice variety used and the presence of unproductive tillers in each hill, which may have resulted from late tillering (Reuben et al., 2016), as well as the variety's capacity to cope with stress, particularly in CF conditions. (Mallareddy et al., 2023)

Table 11: Average number of panicles per hill for AWD and CF treatments

Treatment	Blocks		
	1	2	3
AWD-S1	10	10	11
CF-S1	11	10	8
AWD-S2	9	10	11
CF-S2	8	9	7

S1=Season 1, S2=Season 2

1.2.7 Number of grains per panicle

There was no significant difference ($p > 0.05$) in the number of grains per panicle between the AWD and CF treatments. This finding suggests that rice transplanted under both treatments performs similarly in terms of the number of grains per panicle. Specifically, the number of grains per panicle in the AWD plots ranged from 214 to 239, while in the CF plots, it ranged from 208 to 235. As shown in Table 12, the average number of grains per panicle was 219 for AWD-S1, 217 for CF-S1, 222 for AWD-S2, and 219 for CF-S2. Thus, the overall average number of grains per panicle for both seasons was 220 for the AWD plots and 218 for the CF plots. Reuben et al., (2016) obtained an average number of 136.6 grains per panicle under AWD for plant spacing of 20cm x 20cm. The difference might be due to varieties used and agronomic practises during cultivation.

Table 12: Average number of grains per panicle for AWD and CF treatments

Treatment	Average number of grains per panicle
AWD-S1	219
CF-S1	217
AWD-S2	222
CF-S2	219

S1=Season 1, S2=Season 2

1.2.8 Yield

The average fresh yield weight for both seasons was 1.65 kg/m² (1.65 t ha⁻¹) and 1.45 kg/m² (145 t ha⁻¹) for the AWD and CF water regimes, respectively, while the dry yield weight was 1.52 kg/m² (1.52 t ha⁻¹) and 1.33 kg/m² (1.33 t ha⁻¹), respectively (Table 13). The moisture content for freshly harvested rice and the dried one were 21% and 14%, respectively. The analysis of variance showed no significant difference ($p > 0.05$) but a slight variation in yield between treatments, which may be attributed to minor variation in the number of productive tillers, panicles, and grains among plots. Huang et al. (2024) reported rice grain yields ranging from 11.8 to 14.5 t ha⁻¹ in 2021 and from 12.9 to 15.5 t ha⁻¹ in 2022, with respective averages of 13.4 and 14.0 t ha⁻¹. These findings show that there are several ways to achieve extremely high rice yield, and two of them are increasing grain weight and panicles per square meter.

Table 13: Fresh and dry yield weight for AWD and CF treatments

Treatment	Fresh weight (t ha^{-1})	Dry weight (t ha^{-1})
AWD-S1	17.63	16.19
CF-S1	16.46	15.12
AWD-S2	15.43	14.17
CF-S2	12.48	11.46

S1=Season 1, S2=Season 2

1.2.9 Water footprint of rice

The results reveal clear, statistically significant differences ($p < 0.05$) between the consumptive water footprints (WF) of the alternate wetting and drying (AWD) treatment and the continuous flooding (CF) treatment across two cropping seasons (Table 14). In Season 1, AWD exhibited a total consumptive WF of 0.1419 m³/kg (141.9 m³/ton), which was markedly lower than the 0.2936 m³/kg (293.6 m³/ton) observed for CF which is a difference of 0.1517 m³/kg. This represents a 52% reduction in total WF for AWD compared to CF. Similarly, in Season 2, the total WF for AWD (0.2356 m³/kg or 235.6 m³/ton) was 0.1621 m³/kg less than that of CF (0.3977 m³/kg or 397.7 m³/ton), amounting to a 41% reduction.

Breaking down these WFs into their blue and green components further underscores AWD's comparative efficiency. In Season 1, AWD's consumptive blue and green WFs were 0.1296 and 0.0122 m³/kg, respectively, whereas CF recorded 0.2804 and 0.0132 m³/kg. Although both irrigation methods showed elevated values in Season 2, AWD remained consistently lower than CF. Across both seasons, AWD's average total WF (blue plus green) was 0.1887 m³/kg (188.7 m³/ton), in contrast to CF's 0.3457 m³/kg (345.7 m³/ton).

These findings align with other research indicating that AWD generally reduces water use relative to CF. Punyawansiri et al. (2020), for example, reported similar trends but found higher absolute values for both treatments (ranging from 802 to 931 m³/ton under AWD and 1,067.3 to 1,171.3 m³/ton under CF). Discrepancies among studies can often be attributed to differences in rice varieties, local climate, soil properties, and field management practices, all of which influence total water requirements and consumption.

Statistical tests confirmed that the differences between AWD and CF were significant ($p < 0.05$) not only for the overall consumptive WF but also for water productivity and water-use efficiency. AWD achieved an average water productivity of 5.38 kg/m³, exceeding CF's 2.95 kg/m³ by a wide margin, and its overall water-use efficiency was 75%, as opposed to 41% for CF. These improvements led to an average water savings of about 65.8% over the two seasons. The substantial effect sizes observed reinforce the conclusion that AWD is significantly more water-efficient than CF, making it a compelling option for enhancing water conservation and crop productivity—particularly in regions where water resources are increasingly constrained.

Table 14: Water footprint of rice under AWD and CF irrigation techniques for 2 seasons

Treatments	Water footprint (m³/kg)			
	WF_{Blue}	WF_{Green}	Total	Average
AWD-S1	0.1296	0.0122	0.1419	0.1887
AWD-S2	0.1722	0.0634	0.2356	
CF-S1	0.2804	0.0132	0.2936	0.3457
CF-S2	0.3088	0.0889	0.3977	

1.3 Conclusion and recommendations

The study aimed to identify a water application method that either increases or maintains rice yields while reducing overall water use, specifically by comparing the Alternate Wetting and Drying (AWD) and Continuous Flooding (CF) irrigation techniques. This focus emerged from the recognition that existing water resources are insufficient to irrigate all cultivated land, and many farmers continue to rely on conventional methods leading to excessive water losses due to limited knowledge or access to cost-effective alternatives.

The findings show that AWD offers a significantly lower water footprint, higher water-use efficiency, and greater productivity than CF, resulting in a 65.8% water savings. By contrast, CF demonstrated lower efficiency and greater water loss from the fields. These results can inform the efforts of irrigation associations, the National Irrigation Commission, and agricultural extension officers in formulating improved water management strategies that enhance both yields and resource sustainability.

Farmers should adopt AWD and best practices like correct tillage, optimal plant spacing, proper use of fertilizers and insecticides, and effective weed control to maximize yields. Additionally, improving irrigation scheme infrastructure is essential to minimize water losses and ensure efficient distribution. While disseminating knowledge about crop water requirements can be challenging, agricultural and irrigation experts must explore innovative communication methods to facilitate the widespread and successful adoption of AWD.

Conflict of interest

The authors declare that they don't have conflict of interest.

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