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Development of a Semi-Automated Drip Irrigation System to Enhance Water Productivity and Tuber Yield of Gajah Cassava under Rainfed Conditions

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Cassava productivity in rainfed tropical regions is declining due to prolonged dry seasons and increasingly unpredictable rainfall patterns. In this study, we address these challenges by evaluating the application of a semi-automatic drip irrigation system combined with earlier planting times in the dry season. The goal is to increase yields and water use efficiency (WUE) in Gajah cassava varieties. In this field research, two treatments were compared: (P1) planting at the beginning of the dry season with drip irrigation support during the vegetative phase, and (P2) planting at the beginning of the rainy season conventionally without irrigation. Results showed that P1 significantly outperformed P2, achieving a 42.4% higher yield (110.95 tons/ha vs. 77.94 tons/ha) and a 34% improvement in WUE (4.896 kg/m³ vs. 3.654 kg/m³). In treatment P1, supplemental irrigation only covered 2.84% of the total water input, indicating its efficiency in mitigating early drought stress and supporting initial crop growth. Statistical analysis showed a significant difference in yield ($p < 0.05$), with P1 showing a higher response despite greater variability. These findings support the implementation of precision agriculture strategies that integrate planting schedules with seasonal rainfall patterns and targeted irrigation use. The semi-automated system, powered by solar panels and grid electricity, provides a scalable, cost-effective solution, particularly suitable for small-scale farmers in semi-arid and hilly areas. Future research should assess the long-term effects across agroecological zones. Additionally, irrigation protocols need refinement for different cassava growth stages. This integrated approach contributes to climate-smart agriculture by improving resource efficiency, crop resilience, and sustainability in water-limited environments.
Keywords: Climate-smart agriculture, water productivity, precision irrigation, rainfed cropping systems, smallholder innovation.

INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a strategic commodity for food security and industrial crops in tropical and subtropical regions. Its key advantages include high carbohydrate content, versatile processing potential, and resistance to suboptimal land (Ceballos et al., 2006; Kaur & Ahluwalia, 2017; Li et al., 2017). Its ability to withstand drought and grow in nutrient-poor soil makes cassava a very important commodity in developing countries, both as a mainstay of rural life and national food security (Fathi & Kardoni, 2020). In addition to its main role as food and livestock feed, cassava is also used for starch, bioethanol, and other bio-based products. This potential encourages various initiatives to improve its nutritional value and industrial characteristics (Ferraro et al., 2016). In addressing increasingly unpredictable climate variability, our active role in implementing adaptive technologies such as drip irrigation

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systems combined with early dry-season planting is a determining factor in maintaining cassava productivity (Sunitha et al., 2013; Xie et al., 2020). This study explores the development and performance of a semi-automated drip irrigation system to enhance water use efficiency and tuber yield in Gajah cassava under rainfed conditions (Hanson & May, 2004; Kimaro, 2019). Rainfall has shown a significant increase since November, reaching its maximum of 640.7 mm in January 2024, which marked the wettest phase of the growing season (see Figure 1). Following this peak, there was a consistent decrease in rainfall, reaching a record low of just 0.2 mm by August 2024. Although there was a slight increase to 73.8 mm in October, this proved insufficient to prevent extreme drought conditions during the crop's generative phase. This trend demonstrates how supplemental irrigation, especially semi-automated drip systems, plays an indispensable role in maintaining reliable water availability throughout prolonged dry periods. Its application becomes especially important during critical months like August and September to sustain crop growth and preserve yields amid increasingly unpredictable climate conditions.

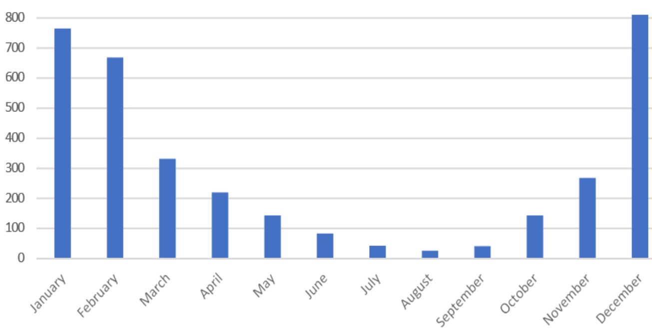

Figure 1. Average monthly rainfall pattern during the cassava growing season (2020–2024) (Data source: BMKG Online Data [https://dataonline.bmkg.go.id/data-harian]).

As shown in Figure 1, these seasonal dynamics highlight the critical role of supplemental irrigation in maintaining a stable water supply, especially during the dry months of September, October, and August, to support plant growth and secure yield under increasingly erratic rainfall conditions (Pacheco et al., 2020). This reinforces the importance of synchronizing crop phenology with climatic patterns, a principle at the core of climate-smart agriculture for cassava in tropical uplands (Gbadebo Olubukola Victory et al., 2022; Victory et al., 2022). Despite the promising potential of drip irrigation and early dry-season planting, several critical issues require further study to optimize cassava productivity under rainfed onditions (Janket et al., 2020; Mahakosee et al., 2022; Wasonga et al., 2020). One key concern is the limited understanding of cassava's water requirements at different phenological stages, especially during the generative phase when tuber initiation and bulking are highly sensitive to water stress (El-Sharkawy, 2007). Water deficits occurring during this growth stage seriously disrupt biomass accumulation and suppress crop productivity potential (El-Sharkawy, 2012). Furthermore, the interaction between planting patterns, irrigation intensity, and rainfall fluctuations in semi-arid and rainfed areas have not been widely explored, hindering the formulation of precision irrigation guidelines (Alvarez, 2012).

A comprehensive evaluation of the long-term impacts of semi- automated drip irrigation systems is imperative, particularly regarding soil moisture dynamics, nutrient uptake efficiency, and production consistency across diverse agroecological zone types (Rastogi et al., 2024). Addressing these gaps is crucial for designing water-efficient, context-appropriate cultivation strategies to enhance cassava resilience and productivity amid changing climatic conditions. To address water scarcity in rainfed cassava cultivation, this study proposes an integrated approach combining early-season drip irrigation during the vegetative phase with strategic planting schedules, ensuring the reproductive phase aligns with the onset of the rainy season. This approach is based on the premise that optimal vegetative development will promote efficient tuber formation and enlargement along with increased water supply (Van Duivenbooden et al., 2000; Hammer et al., 2004). The semi-automatic drip irrigation system is able to optimize water efficiency while implementing the principles of precision agriculture by ensuring efficient use of resources and at the required time (Abuzanouneh et al., 2022; Ponnusamy & Natarajan, 2021). This method has great potential to enhance the efficiency of water use in cassava cultivation while creating opportunities for more sustainable agricultural practices with higher productivity (Amusan & Oyewole, 2023; Ayars et al., 2001; dos Santos Silva et al., 2019; Vitor et al., 2019). The integration of drip irrigation and strategic early dry-season planting, as implemented in our study, promotes optimal early vegetative development, thereby allowing for efficient exploitation of natural precipitation during the critical tuber bulking phase (Hammer et al., 2004; Zubelzu et al., 2023). This approach is in line with the principles of precision agriculture through increasing the timeliness and efficiency of resource use (Amusan & Oyewole, 2023; Erickson & Fausti, 2021).

Research findings show that optimal early vegetative formation contributes to increased tuber productivity through better root and canopy system development, thereby increasing nutrient and water absorption in the generative phase (Van Duivenbooden et al., 2000; Hammer et al., 2004). The semi-automatic drip irrigation system is an economical and easily adaptable solution for small-scale farming to deal with the dry season, while also confirming its position as an agricultural innovation that is adaptive to climate change (Amusan & Oyewole, 2023; Ayars et al., 2015; Difallah et al., 2017). One of the main problems faced is the still limited understanding regarding the water requirements for cassava plants at various phenological stages, especially during the generative phase when tuber initiation and enlargement are very vulnerable to water deficits (El-Sharkawy, 2007; Hernández-Ochoa et al., 2022; Sruthy & Arjun, 2023). Water deficits during this growth stage can seriously disrupt the biomass accumulation process and suppress the plant's productivity potential (Dietz et al., 2021; El-Sharkawy, 2012; Qin et al., 2023). In addition, the interaction between planting schedules, irrigation frequency, and rainfall variability in semi-arid and rainfed systems has not been widely studied, thus hampering the preparation of precise irrigation guidelines (Alvarez, 2012; García et al., 2020; Souza et al., 2020). It is also necessary to evaluate the long-term impact of semi-automatic drip irrigation on soil moisture dynamics, nutrient uptake, and yield stability in various agroecological zones (Rastogi et al., 2024). It is also necessary to evaluate the long-term impact of semi-automatic drip irrigation on soil moisture dynamics, nutrient uptake, and yield stability in various agroecological zones. This study has three main objectives. The first objective is to examine the effectiveness of the application of a semi-automatic drip irrigation system in the vegetative growth phase to increase the productivity and efficiency of water use of Gajah cassava plants in a rainfed cultivation system. Second, this study aims to compare the performance of yields and water productivity between early dry season planting strategies with drip irrigation support and conventional early rainy season planting strategies without irrigation. Third, this study aims to assess the potential for integrating strategic planting schedules with precision irrigation interventions as an effort to increase tuber yields and strengthen plant resilience in environments facing prolonged dry season water constraints. This research has important significance because it offers a practical solution to increase cassava productivity in rainfed tropical areas through a combination of early dry season planting with semi-automatic drip irrigation. In addition, this research addresses challenges related to water scarcity and climate variability, especially during critical growth stages. This approach supports climate-smart agriculture by increasing water use efficiency and crop yields, especially for small- scale farmers. Its cost-effective and easily replicable design makes the system suitable for widespread adoption, supporting the realization of a sustainable and highly resilient cassava cultivation system.

MATERIALS AND METHODS

This study was conducted on flat land located in Tamalanrea Jaya Subdistrict, Makassar City, South Sulawesi, Indonesia, at geographical coordinates 5°08.420' South Latitude and 119°29.790' East Longitude. The site falls within a humid tropical climate zone classified as type C according to the Koppen-Geiger system, characterized by two distinct seasons: the rainy season (December–May) and the dry season (June–November). To support the agroclimatic context of the experimental design, annual rainfall variability data from 2015 to 2024 is also presented. The soil at the research site is classified as reddish-brown latosol with a sandy clay texture. This type of soil exhibits moderate fertility and good drainage capacity. These characteristics justify the site's suitability for cultivating tuber crops such as cassava, which requires well-aerated soil that retains moisture without becoming waterlogged. The experimental design followed a Completely Randomized Design (CRD) consisting of two main treatments. The first treatment (P1) involved cassava planting at the beginning of the dry season (September), supported by a semi-automatic drip irrigation system during the vegetative phase (days 1–90 after planting), while the generative phase relied entirely on natural rainfall. The second treatment (P2) was planted at the onset of the rainy season (December) without any irrigation, meaning plant growth depended solely on rainfall, including during the generative phase that occurred in the subsequent dry season. Each treatment was replicated four times, resulting in a total of eight experimental units. Planting layout and density were designed uniformly across all experimental units. Each plot consisted of six parallel rows of drip tape, each 13 meters long. In each row, 20 cassava cuttings were planted with a spacing of 60 cm between plants and 1.75 meters between rows. Planting holes were prepared at a depth of 15–20 cm and a diameter of 30–40 cm, and each was filled with a soil mixture and 5 liters of rice husk to improve aeration and ensure uniform planting medium. Cuttings were planted vertically to a depth of approximately 10–12 cm, with two nodes embedded in the soil. The semi-automatic drip irrigation system was designed using key components including a 12V DC water pump, a water tank with a capacity of 300–1000 liters, an automatic float switch to regulate water level, a programmable 12V digital timer, and a 12V solenoid valve to control water flow automatically. Electrical power for the system was provided by a 20–50W solar panel, with energy stored in a 12V 7Ah VRLA battery. Water was distributed through PE or PVC pipes to 16 mm-diameter drip tapes, with emitters positioned 5–7 cm from the plant base to ensure water delivery directly to the root zone. For the P1 treatment, irrigation during the vegetative phase was applied according to a pre-set schedule using a digital timer. From day 1 to 30, each plant received 0.5 liters of water over 30 minutes (5:00–5:30 PM). From day 31 to 60, irrigation increased to 0.75 liters per plant over 45 minutes (5:00–5:45 PM). From day 61 to the start of the rainy season, 1 liter of water was applied per plant over 60 minutes (5:00–6:00 PM). The total irrigation volume during the vegetative phase amounted to 67.5 liters per plant, equivalent to only about 2.84% of the estimated total seasonal water requirement for cassava. To enhance operational flexibility, the system was equipped with a manual valve as a bypass feature, allowing farmers to conduct additional manual watering when needed, especially if plants show signs of water stress or if unexpected weather changes occur outside the scheduled irrigation. To facilitate reader understanding of the irrigation system structure, Figure 2 is included to present a schematic diagram of the semi-automatic drip irrigation system used in treatment P1. Additionally, Table 1 provides a detailed breakdown of each system component, including specifications and respective functions in supporting the irrigation process.

***Experimental design*:** The study employed a Completely Randomized Design (CRD) to evaluate the effects of planting time and water availability on the yield of Gajah cassava. The study consisted of two main treatments, each replicated four times, resulting in a total of eight experimental units. This method allowed for controlled comparisons and minimized the influence of external variables. The first treatment (P1) involved planting Gajah cassava during the onset of the dry season (September). During the vegetative phase (days 1 to 90 after planting), plants received supplemental water through a semi-automated drip irrigation system. However, weather largely determines the outcome of the crop. The researchers discontinued irrigation at the start of the rainy season, and the crop relied solely on natural rainfall until it was harvested approximately ten months after planting. The second treatment (P2) commenced with planting at the onset of the rainy season in December. In this scenario, cassava plants relied entirely on rainfall during the vegetative phase. However, the generative phase and tuber development occurred during the subsequent dry season, when the researchers provided no irrigation. This condition rendered the plants more susceptible to water stress, particularly during the critical period of tuber maturation. Each experimental unit was established on flat, homogeneous land and equipped with an irrigation system composed of six parallel drip lines, each measuring 13 m in length. The researchers planted 20 cassava stems along each line, meticulously spaced 60 cm apart, ensuring each plant had ample room to grow. The researchers maintained a 1.75-meter distance between lines to ensure sufficient growing space. Before planting, they prepared each hole to a depth of 15–20 cm and a diameter of 30–40 cm. They thoroughly mixed the soil in each hole with 5 liters of rice husks to create a loose and uniform planting medium. The research team vertically inserted the cassava cuttings to a depth of 10–12 cm and buried two nodes within the soil–rice husk mixture. They centered each cutting to optimize root development. At 60 days after planting, they applied 5 grams of NPK 16:16:16 fertilizer to each plant in a circular pattern about 15 cm from the stem base to promote vegetative growth. They arranged the planting layout to ensure balanced spacing, uniform water distribution, and optimal nutrient availability for all plants. The researchers positioned the water emitters on the drip lines 5–7 cm from the base of each plant, aligning them with the root zone. They controlled the drip irrigation system semi-automatically using a timer, which they manually reprogrammed for each growth stage. Specifically, they set the timer to deliver 0.5 liters per plant per day for 30 minutes (17:00–17:30) during days 1–30, 0.75 liters for 45 minutes (17:00–17:45) during days 31–60, and 1 liter for 60 minutes (17:00–18:00) from day 61 until the rainy season began. To increase adaptability to water shortage conditions, the team installed a manual valve as a bypass system to provide supplementary irrigation when needed, without being tied to a fixed irrigation schedule. With this feature, we can adjust to the fluctuations in the hydrological needs of plants, which plays a vital role in ensuring optimal growth in the field environment. This study was designed to compare the growth and yield of cassava plants receiving irrigation during the vegetative phase with those relying solely on rainfall. Additionally, the research examines the extent to which water availability during the generative phase influences tuber formation and the plant's final productivity.

***Material*:** The main material used in this study was a semi-automated drip irrigation system designed to optimize water use efficiency in rainfed cassava cultivation. This system combines renewable and conventional energy sources, utilizing both solar power and electricity from the national grid (PLN) to ensure reliable operation under various field conditions. At its core, a 12V DC water pump function to channel water from the main source into a reservoir tank. The water level in the tank is automatically regulated by a float switch, preventing both overflow and underfilling. The pump is powered by a rechargeable battery, which receives energy from a solar panel. The battery charging process is regulated by a charge controller to ensure a stable energy supply. The irrigation schedule is managed by a programmable digital timer that automatically controls the opening and closing of a solenoid valve based on the crop's water requirements. Water is delivered precisely through a network of distribution pipes and drip tapes, ensuring adequate moisture directly at the plant root zone. This system design supports efficient water management and aligns with the principles of precision agriculture, making it a sustainable and widely applicable solution, especially for smallholder farmers in areas with limited water availability. To enhance operational flexibility, the system is also equipped with a 220V to 12V adapter, allowing it to operate using grid electricity (PLN) when solar energy is insufficient. Shut-off valves are installed along the branch distribution lines, enabling manual adjustment of water flow to specific sections as needed. This design supports both automated and manual operation, making it a practical and adaptable solution for various field conditions. The system ensures timely and efficient irrigation at every stage of plant growth, while still allowing for manual intervention when necessary. A schematic diagram illustrating the system configuration for Treatment P1 is presented in Figure 2.

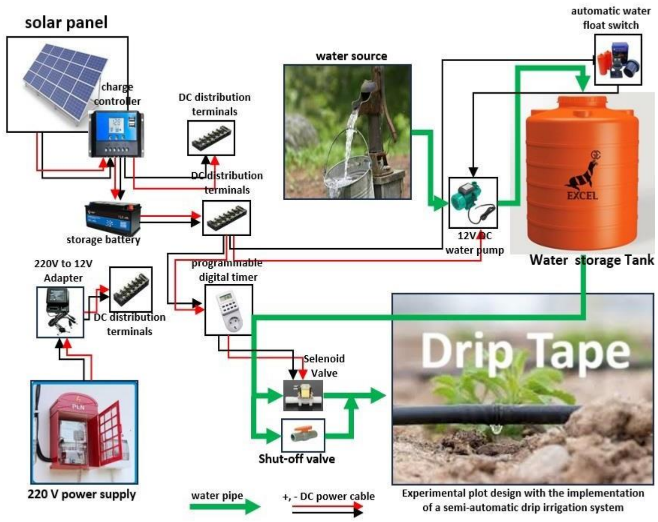

Figure 2. Schematic diagram of the semi-automatic drip irrigation system used in treatment P1.

Table 1 presents a list of the main components used in the semi-automatic drip irrigation system, along with their technical specifications and functions. This system is designed to optimize water use efficiency in crop cultivation by integrating simple automation technologies such as digital timers, float switches, and solar power. All components work synergistically to deliver precise water supply, reduce dependence on grid electricity (PLN), and simplify maintenance. The listed prices are estimates and may vary depending on the brand, quality, and place of purchase. This information can serve as a reference for budget planning or system adjustments as needed. Since prices may change over time, a market survey is recommended prior to making a purchase.

The semi-automatic drip irrigation system begins with the water pumping and storage unit. A 12V DC water pump function to draw water from a source, such as a well or rainwater reservoir, into a water storage tank. The pumped water is stored in a tank with a capacity ranging from 300 to 1000 liters, typically made of plastic or fiber materials. To maintain an optimal water level, the system is equipped with a 12V float switch that automatically activates or deactivates the pump when the water level reaches a predetermined threshold. Next, the irrigation schedule is controlled automatically through a programmable 12V digital timer. This timer sends signals to a 12V solenoid valve to open or close the water flow according to the preset schedule. The solenoid valve, with a 1/2-inch diameter, precisely regulates the water flow, allowing the system to operate without direct supervision. In addition, a manual valve is provided as a backup option for manual watering, especially when plants show signs of water stress or require irrigation outside the automatic schedule. The electrical energy to operate the system is supplied by a 20–50 watt solar panel with a 12V output. This panel provides power that is stored in a 12V, 7Ah VRLA (Valve Regulated Lead Acid) battery, allowing the system to continue operating even in the absence of sunlight. To ensure stable and safe battery charging, a PWM-type charge controller with a capacity of 10A–20A and a 12V input voltage is used. As a backup, the system is also equipped with an adapter that converts 220V AC mains electricity to 12V DC, ensuring continued operation when solar power is

Table 1. Components, specifications, and functions of the semi-automatic drip irrigation system.

No.	Component	Specification	Function
1	DC 12V Water Pump	12V DC voltage, flow capacity ±1–2 L/min	Pumps water from the source to the water tank
2	Water Tank	Volume 300–1000 liters, made of plastic or fiber	Stores water before distributing to the irrigation system
3	Automatic Float Switch	12V voltage, float type	Automatically controls the water level in the tank
4	Digital Timer	12V voltage, programmable, daily interval	Controls irrigation timing according to the set schedule
5	12V Solenoid Valve	12V DC voltage, 1/2 inch size	Opens and closes water flow automatically based on signals from the timer
6	Solar Panel	Power 20W–50W, 12V output voltage	Provides electrical energy from sunlight
7	Charge Controller	PWM type, 10A–20A capacity, 12V input voltage	Regulates battery charging from the solar panel to prevent overcharging
8	12V 7Ah Battery	12V voltage, 7Ah capacity, VRLA type	Stores electrical energy to operate the system when there is no sunlight
9	Drip Tape	Diameter 16mm, hole spacing 60cm, 50m roll length	Delivers water evenly to each plant through direct droplets at the root zone
10	Distribution Pipe	PE/PVC, diameter 1/2 inch – 1 inch, length as needed	Channels water from the tank to the drip tape
11	Manual Valve	1/2 inch size, made of plastic or metal	Provides option for manual watering when needed, especially when plants show water stress
12	220V to 12V Adapter	Input 220V AC, output 12V DC, 5A–10A capacity	Converts mains electricity to 12V DC to operate the system when solar power is insufficient
13	Shut-off Valve	1/2 inch – 1 inch size, made of plastic or metal	Stops or regulates water flow manually in main or branch distribution lines

insufficient. Water distribution to the plants is carried out through PE or PVC distribution pipes with diameters ranging from 1/2 inch to 1 inch, channelling water from the tank to the drip tape. The drip tape, with a diameter of 16 mm, 60 cm emitter spacing, and a roll length of 50 meters, is designed to deliver water directly and evenly to the plant root zone. For additional control over water flow in the main or branch distribution lines, a shut-off valve is installed, enabling users to manually stop or adjust water flow as needed.

***Data collection*:** The study analyzed the data to evaluate the productivity of Manihot esculenta Crantz variety Gajah by measuring key yield components at harvest during the 2023–2024 cultivation period. They measured total fresh tuber yield per hectare (tons/ha), average fresh tuber weight per plant (kg/plant), and average tuber length and diameter (cm). Using a measuring tape, they measured the length from the base to the tip of the largest tuber, while a digital caliper helped them determine the diameter at its thickest point. To calculate the total yield per hectare, researchers summed the yield from sample plots and extrapolated the results to a one-hectare scale. In treatment P1, which applied the semi-automatic drip irrigation system, the research team also monitored environmental parameters to assess system performance and water availability for the plants. They collected daily rainfall data from the nearest agroclimate monitoring station and manually recorded the irrigation volume discharged from the storage tank during each irrigation session. These records enabled the evaluation of irrigation adequacy and its role in supporting plant development and maximizing yield under rainfed conditions.

***Statistical analysis*:** The study employed statistical analysis to evaluate the impact of various treatments on cassava productivity. Prior to comparing treatments, the data were tested for normality using the Shapiro–Wilk test and for homogeneity of variance using Levene's test. These preliminary tests ensured that the data met the fundamental assumptions required for parametric analysis. Since the data were confirmed to be normally distributed with equal variances across groups, the researchers proceeded with an independent samples t-test to evaluate differences between treatment P1 (drip irrigation with early dry-season planting) and treatment P2 (early rainy-season planting without irrigation). All statistical tests were conducted at a 5% significance level (α = 0.05) using standard analytical software.

Based on the study's objective, which was to examine the effectiveness of drip irrigation–based strategic planting system in enhancing cassava productivity under dry-season conditions, the researchers formulated two hypotheses. The null hypothesis (H_0) stated that there is no significant difference in cassava productivity between treatment P1 and treatment P2. In contrast, the alternative hypothesis (H_1) posited that cassava productivity under treatment P1 is significantly higher than under treatment P2. This hypothesis guided the analysis in determining whether integrating irrigation with early planting could provide a measurable yield advantage, particularly in environments with seasonal water deficits.

RESULTS

***Irrigation effectiveness*:** The implementation of a semi-automated drip irrigation system during the vegetative phase proved to be highly effective in enhancing cassava productivity and water use efficiency (WUE) under rainfed conditions. In Treatment 1 (P1), cassava plants received approximately 67.5 liters of supplemental irrigation per plant, resulting in a yield of 110,952 kg/ha and a WUE of 4.896 kg/m³. This represents a 42.4% increase in yield and a 34% improvement in WUE compared to Treatment 2 (P2), which relied solely on rainfall and produced only 77,936 kg/ha with a WUE of 3.654 kg/m³. Notably, the additional irrigation volume in P1 accounted for only about 2.84% of the total water input, yet it led to a substantial increase in harvest yield. This finding highlights the efficiency of precision water delivery directly to the root zone during the critical vegetative phase, where moisture is essential for uniform stand establishment and canopy development. The data summarized in Table 3 clearly demonstrates that despite receiving nearly the same total water volume, P1 significantly outperformed P2 in both yield and water use efficiency. These results validate the use of drip irrigation not only as a yield-enhancing measure but also as a water-conserving strategy, especially relevant in semi- arid or dryland environments.

Table 2. Comparison of Water Use Efficiency (WUE) in cassava plants with and without drip irrigation.

Treatment	Production (kg/ha)	Volume (m³/ha)	WUE (kg/m³)
P1 (Irrigation + Rain)	110,952	22,663.37	4.896
P2 (Rain Only)	77,936	22,020.00	3.654

Table 2 further illustrates the comparison of average productivity and tuber characteristics between the two treatments. P1 not only produced a higher mean yield but also exhibited greater variability and high-end outliers, suggesting greater responsiveness to favorable conditions and management practices. The broader yield distribution in P1 indicates strong potential under optimized inputs, while P2 displayed more stable yet lower yields, representing a yield ceiling in rain-dependent systems. Figure 3 below presents the detailed data on cassava productivity per planting order and plot for each treatment group. The data illustrates the consistent superiority of P1 across three drip- irrigated plots, with average per-plant yields ranging from 11.60 to 11.70 kg. In contrast, yields from the control plots in P2 ranged between 7.95 and 8.35 kg/plant.

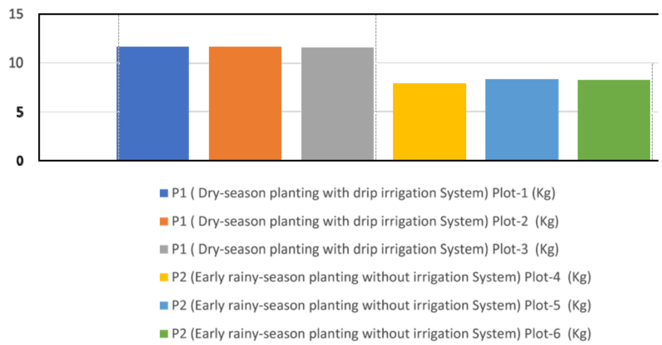

Figure 3. Bar chart comparing the average productivity and tuber characteristics between P1 and P2.

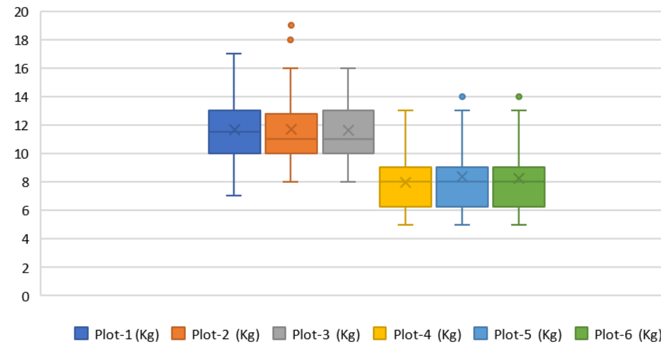

Figure 4. Boxplot of tuber weight distribution for each treatment.

Figure 3 visualises the comparison and reinforces the agronomic advantage of applying semi-automated drip irrigation during early growth stages. Although P1 showed more variation, including extreme values up to 19 kg per plant, this is attributed to high responsiveness to water and nutrient availability rather than inconsistency. Conversely, the predictability of yields in P2, as seen in the tighter clustering, should reassure farmers about the reliability of semi-automated drip irrigation, albeit at the expense of higher yield potential and water productivity.

***Comparative evaluation of treatment effects on cassava productivity*:** The comparison between P1 (dry-season planting with drip irrigation) and P2 (early rainy-season planting without irrigation) revealed statistically significant differences in cassava productivity. On average, P1 produced 11.65 kg of fresh tubers per plant, whereas P2 produced only 8.18 kilograms, a difference of 3.47 kg per plant. Scaled to a hectare, this equated to 110,952 kg/ha in P1 versus 77,937 kg/ha in P2. An independent samples t-test confirmed the significance of these differences ($t = 9.21$, $p < 0.05$), indicating that the superior performance of P1 was not due to random variation. While P1 had slightly greater yield variability (SD = 2.3 kg/plant) than P2 (SD = 1.8 kg/plant), its yield potential was markedly higher. Histogram and boxplot analyses further illustrated that P1 had a wider yield distribution with high-end outliers (up to 19 kg/plant), while P2 showed more clustered, predictable yields (typically 8–9 kg/plant). These findings demonstrate that P1 offers a substantial productivity advantage but may be more sensitive to environmental or management factors. In addition to the tabular data, Figure 4 provides a visual comparison of the yield distribution in the form of a boxplot, clearly showing that P1 has a wider interquartile range and several high-yield outliers, with values reaching up to 19 kg per plant. This suggests higher yield potential under optimal conditions. Meanwhile, P2 exhibits a narrower and more symmetrical distribution with a lower median and no significant outliers, indicating more stable but limited productivity.

Figure 4 shows the visual and statistical results reinforce the interpretation that while P1 offers higher productivity, it also displays greater variability, potentially reflecting its sensitivity to microenvironmental and management differences.

***Evaluation of integrated planting and irrigation strategy*:** The integrated approach of combining strategic early dry-season planting with a semi- automated drip irrigation system offers a robust, climate-adaptive solution for cassava cultivation in tropical rainfed environments. By initiating planting in early September, at the onset of the dry season, and applying supplemental irrigation during the critical vegetative phase, cassava plants can establish strong root systems and vigorous canopy structures under managed water conditions. This physiological foundation enables the crop to fully capitalize on the onset of the rainy season during the generative phase, particularly tuber initiation and bulking when water demand peaks. As a result, the system reduces the risk of water stress during yield- determining stages and optimizes growing conditions without requiring continued irrigation into the later stages of growth. This approach is strongly supported by agroclimatic data observed during the 2023–2024 cassava cultivation cycle. Figure 6 below presents the monthly rainfall distribution recorded during the study period, highlighting the minimal rainfall in September (0 mm) and October (7.5 mm), followed by a significant increase starting in November and peaking in January 2024 at 640.7 mm. This clear seasonal pattern validates the decision to shift planting to the dry season with targeted irrigation, ensuring that the high water demand of the generative phase optimistically coincides with abundant natural rainfall.

Figure 5 illustrates the integration of irrigation technology and planting schedule not only improved cassava productivity and water use efficiency but also enhanced the crop's resilience to prolonged dry spells. While Treatment 2 (P2) demonstrated more consistent but lower yields due to its dependence on natural rainfall throughout the cycle, Treatment 1 (P1) leveraged this integrated strategy to achieve significantly higher yields with minimal additional water input. Therefore, this model offers a scalable and practical example of climate-smart agriculture, particularly relevant for smallholder farmers in semi-arid or upland tropical regions where rainfall is highly seasonal and erratic.

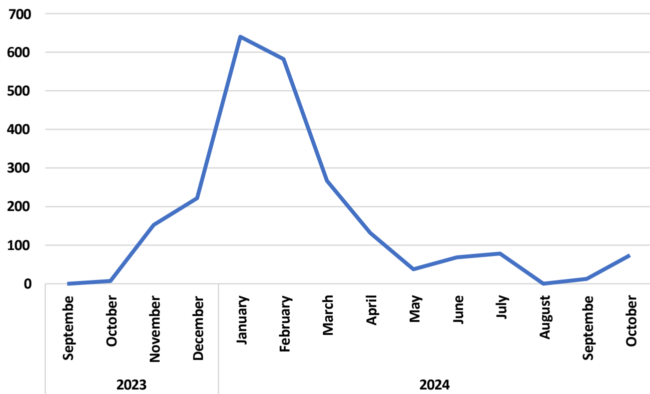

Figure 5. Monthly rainfall chart during the cassava planting period (Data source: BMKG Online Data [https://dataonline.bmkg.go.id/data-harian]).

DISCUSSION

***Yield enhancement through strategic planting and irrigation*:** The integration of early dry- season planting with semi-automated drip irrigation (P1) significantly enhanced cassava productivity, resulting in a 42.4% increase in yield and a 34% improvement in water use efficiency (WUE) compared to the conventional early rainy-season planting without irrigation (P2). This substantial yield gain underscores the crucial role of providing supplemental water during the vegetative phase, particularly in rain-fed environments where early drought stress can hinder plant establishment and future tuber formation. The strategic timing of planting in September, before the rainy season, enabled cassava plants in P1 to develop a robust root system and vegetative canopy under controlled irrigation, thereby improving their physiological capacity to absorb nutrients and water during the generative phase when rainfall peaked. This aligns with agronomic principles, which indicate that vigorous early-stage growth strengthens source-sink dynamics, thereby optimizing carbohydrate partitioning toward storage roots during tuber bulking (Chiewchankaset et al., 2022; Van Duivenbooden et al., 2000; El- Sharkawy, 2007). These findings are consistent with previous studies, which demonstrate that targeted irrigation during early development phases significantly increases yield and water use efficiency (WUE) in root and tuber crops. For example, Alshallash et al. (2023) reported that drip irrigation applied during critical growth stages can improve water use efficiency by delivering water directly to the root zone, reducing evaporation losses, and maintaining stable soil moisture. Similarly, Kurgat et al. (2020) highlighted that in semi-arid regions, early and precise water application supports optimal biomass accumulation, which ultimately leads to increased tuber yield. This study reinforces previous findings by showing that even a very small amount of supplemental irrigation, only about 2.84% of the total water requirement, can lead to significant productivity gains when combined with an appropriate planting schedule. This integrated strategy is highly relevant in the face of increasing climate variability, which causes unpredictable rainfall patterns and prolonged dry periods during critical stages of crop growth. By aligning crop growth phases with the rainy season through early planting and early-stage irrigation, farmers can reduce the risk of early drought stress while maximizing the use of natural rainfall during the tuber development phase. This crop scheduling approach is a climate-adaptive strategy that not only enhances yield stability but also strengthens the resilience of smallholder cassava farming systems, which are generally vulnerable to climate risks. Synchronizing planting time with water availability serves as a fundamental principle of climate-smart agriculture, promoting more sustainable and productive farming systems in tropical rainfed regions (Amusan & Oyewole, 2023; Erickson & Fausti, 2021; Hammer et al., 2004).

***Water productivity and efficiency gains*:** The results of this study highlight the important role of semi-automated drip irrigation in improving water productivity while ensuring efficient use of limited water resources. Although it accounted for only 2.84% of the total water requirement, supplemental irrigation during the vegetative stage in Treatment 1 (P1) significantly increased cassava yield by 42.4%. This level of efficiency demonstrates that targeted watering in the early growth phase can trigger strong physiological responses in cassava, such as optimal canopy development, enhanced root growth, and ultimately greater tuber production. By delivering water directly to the plant's root zone, the semi- automated system minimizes losses through evaporation and runoff, (Obata et al., 2020) ensuring that a small volume of water contributes meaningfully to plant development (Ayars et al., 2015; Hanson & May, 2004). These results reinforce the importance of precision irrigation strategies in dryland and rainfed areas, where water availability is becoming increasingly unpredictable. The use of programmable digital timers and drip lines allows for more accurate irrigation scheduling that aligns with the crop's water needs, making input use more efficient and minimizing waste. Previous studies have also shown that such systems can significantly improve water use efficiency in root and tuber crops by maintaining optimal soil moisture during critical vegetative stages (Amusan & Oyewole, 2023; Difallah et al., 2017). In this study, the observed water use efficiency (WUE) in P1 reached 4.896 kg/m³, outperforming the 3.654 kg/m³ achieved under rain-fed conditions in P2—an increase of 34%. This reinforces the advantage of using small, well-timed volumes of irrigation to support high- yield outcomes in environments prone to dry spells, offering a hopeful solution to water scarcity in agriculture. Moreover, semi-automated drip irrigation is a practical example of climate-smart agriculture that is easy to implement and scalable, especially for smallholder farmers in tropical upland or dryland areas. The system supports the use of renewable energy and has the potential to be integrated with digital tools, such as soil moisture sensors, making it highly suitable for precision agriculture in developing countries (Amusan & Oyewole, 2023; Erickson & Fausti, 2021). By reducing dependence on unpredictable rainfall and enhancing the resilience of cassava cultivation, this technology not only addresses current water scarcity challenges but also prepares farming systems to cope with future climate pressures. Therefore, the design and functionality of this system align with sustainable development goals and support agricultural intensification without compromising environmental sustainability.

***Yield stability vs. responsiveness*:** The results of this study indicate a notable difference between the two treatments in terms of yield variability and stability. Treatment 1 (P1), which combined early dry season planting with a semi-automated drip irrigation system, showed higher yield potential but with greater variability, tuber weights ranged from 8.5 kg to 19 kg per plant. In contrast, Treatment 2 (P2), which relied entirely on rainfall, produced more stable but lower yields, with most tuber weights clustering around 8–9 kg per plant. This pattern illustrates a classic trade-off between high yield potential and yield stability. Treatment P1 can produce significantly higher yields when managed properly and supported by favorable environmental conditions, but it is also more susceptible to microclimatic variations, uneven irrigation distribution, and differences in farmer practices, factors that can lead to yield fluctuations. In contrast, although Treatment P2 produces lower yields, its stability may be more appealing to risk-averse farmers due to its ease of management and more predictable outcomes. These findings are in line with agronomic literature, which suggests that responsive systems, such as precision irrigation, tend to exhibit greater yield variability due to their reliance on precisely managed inputs and environmental feedback (Van Ittersum & Rabbinge, 1997; Pushpalatha et al., 2020). The yield variability observed in P1 is likely due to subtle differences in water distribution, soil structure, or sunlight exposure—factors that can influence crop responses in high-input systems. For smallholder farmers, this variability presents both opportunities and challenges. On one hand, responsive systems can lead to significant gains in productivity and profitability when properly managed. On the other hand, they may increase production uncertainty, especially in situations where farmers face limitations in labor, technical knowledge, or access to maintenance services for irrigation equipment (Altieri et al., 2015; Romero et al., 2022). In the context of technology adoption among smallholder farmers, such trade-offs carry significant implications. Farmers in resource- limited settings tend to prioritize yield stability over maximum yield potential, as crop failure can pose serious financial risks. Therefore, technologies like semi-automated drip irrigation need to be supported by strong extension services, training programs, and advisory systems to ensure that the benefits of responsive systems can be realized without increasing farmers' vulnerability. Institutional support plays a critical role in this process and should not be overlooked. Adaptive strategies such as phased implementation, community-based maintenance schemes, or hybrid systems that combine manual and automated features can help reduce risks while encouraging technology adoption among farmers (Amusan & Oyewole, 2023; Meijer et al., 2015). Thus, the choice between high responsiveness and stable predictability is not merely technical, it is deeply embedded in farmers' perceptions of risk, institutional support, and the long-term security of their livelihoods.

***Agroclimatic synchronization and climate adaptation*:** The rainfall pattern observed during the study period further supports the effectiveness of early dry season planting when combined with a semi-automated drip irrigation system. By planting in September, prior to the onset of heavy rainfall, and applying supplemental irrigation during the vegetative phase, the crop was able to develop a strong canopy and root system before entering the critical tuber bulking stage. Rainfall data showed minimal precipitation in September and October, followed by a sharp increase starting in November and peaking in January. This pattern closely aligned with the cassava plant's highest water demand during the generative phase. The synchronization between the crop's growth stages and the rainy season highlights the crucial role of agroclimatic alignment in enhancing productivity and resilience in rainfed farming systems (Van Duivenbooden et al., 2000; Hammer et al., 2004). The intentions of farmers in Lombok Kulon Village to adopt sustainable organic farming are reflected in their attitudes, subjective norms, perceived behavioral control, moral norms, environmental awareness, and satisfaction with existing policies. Farmers in this village are committed to continuing sustainable organic farming practices. The integration of a well-targeted planting schedule with precision irrigation ensured that the crops did not experience water stress during early growth stages, while also allowing them to benefit from abundant natural rainfall in the later phases. This approach reflects a core principle of climate-smart agriculture: adjusting farming practices to the temporal and spatial variability of climate in order to maximize resource use efficiency and reduce vulnerability to climate change (Amusan & Oyewole, 2023; Kimaro, 2019). As rainfall patterns in tropical regions become increasingly unpredictable due to climate change, aligning planting schedules and crop water requirements with the rainy season becomes a vital adaptation strategy to sustain yields and improve water use efficiency in cassava cultivation. This study provides evidence that such synchronization, when supported by simple irrigation technologies, can serve as a scalable model for adapting cassava farming to climate change in tropical upland and semi-arid areas.

***Limitations of the study*:** This study shows that combining early dry season planting with a semi- automated drip irrigation system is effective in improving cassava productivity. However, this approach also has several limitations. The researchers focused exclusively on the Gajah variety of cassava and experimented on flat land with relatively uniform soil conditions. These choices limit the extent to which the findings of this study can be generalized to other cassava varieties or to areas with sloped or more diverse topographical conditions. Second, although the irrigation system was semi-automated, it still required manual intervention to program the digital timer and monitor system performance, which may pose a challenge for adoption in labor constrained smallholder contexts. Third, external variables, such as localized differences in soil fertility, drainage, and microclimatic conditions, may have influenced plant responses and yield outcomes. These factors highlight the need for caution when extrapolating the results beyond the study area and underscore the importance of further testing across diverse agroecological zones and farming systems to validate the broader applicability of the proposed approach.

***Future research directions*:** Future research should expand on this study by testing the integrated planting and irrigation strategy across a broader range of cassava varieties and agroecological zones to assess its adaptability and performance under diverse environmental conditions. Incorporating soil moisture sensors and advancing the system toward full automation would enhance irrigation precision, reduce labor requirements, and improve scalability, particularly for smallholder farmers with limited resources. Additionally, long-term studies are necessary to assess the long-term effects of repeated semi-automated drip irrigation use on soil health, nutrient uptake efficiency, and multi-season yield stability. Assessing these agronomic outcomes alongside an analysis of economic feasibility and farmer adoption potential will be essential for determining the viability of the system as a sustainable, climate-resilient technology in smallholder production systems. This broader evidence base will support more informed policy recommendations and practical guidelines for implementation at scale.

***Conclusion*:** This study demonstrates that integrating early dry season planting with a semi-automated drip irrigation system significantly enhances cassava productivity and water use efficiency under rainfed conditions. The approach allowed cassava plants to establish robust vegetative growth during dry months and benefit from natural rainfall during the critical tuber bulking phase. Treatment P1 yielded a 42.4% increase in productivity and a 34% improvement in water use efficiency compared to conventional rainfed planting despite requiring only a minimal volume of supplemental irrigation. These findings highlight the potential of precision irrigation and climate-aligned planting schedules to mitigate the risks of seasonal drought and improve the sustainability of cassava production systems. The semi-automated system’s low cost and adaptability make it a viable option for smallholder farmers facing climatic variability in tropical upland and semi-arid regions. The study recommends expanding the use of semi-automated drip irrigation in regions affected by seasonal water shortages. To support this, extension services should focus on training farmers in setting up, operating, and maintaining systems. Future studies should assess the long-term effects of the system on soil health, nutrient uptake, and yield consistency across various cassava types and environments. Enhancing the system with full automation and soil moisture sensors could further improve efficiency. Policymakers and development programs are encouraged to promote this climate-smart solution to strengthen the resilience and sustainability of cassava farming systems.

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***SDGs addressed*:** Zero Hunger; Clean Water and Sanitation; Affordable and Clean Energy; Responsible Consumption and Production

Policy referred: Punjab solar irrigation subsidy (2016); Federal SIP subsidy program (2015); Feed-in Tariff (FIT) policy proposals.

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