Research Article

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Development of a low-cost timer-based drip irrigation system for sustainable Waxy Corn cultivation in El Niño-Prone regions

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Abstract: Water scarcity significantly threatens smallholder agriculture in Indonesia, Exacerbated by El Niño and climate change. Traditional irrigation practices often lead to water inefficiencies and yield losses, particularly in drought-prone regions. This study addresses these challenges by developing and evaluating a unique, low-cost, timer-based, semi-automatic drip irrigation system. This system, tailored for waxy corn farming in South Sulawesi, offers a practical and cost-effective solution for water scarcity. The objective was to enhance water-use efficiency, sustain crop productivity, and assess the economic feasibility of this system as a scalable solution for smallholders in the region. The field experiment, which adjusted irrigation scheduling based on plant growth stages and compared it to conventional practices, yielded promising results. The system achieved a water-use efficiency of 3.87 kg/m^3, categorized as 'good to outstanding,' and delivered consistent yields while reducing manual labor and water wastage. The short payback period of 1.4 planting cycles makes it financially accessible for smallholder adoption, further highlighting the potential impact of the system. This system offers a practical alternative to high-tech sensor-based models, bridging the gap between advanced irrigation technologies and the needs of resource-constrained farmers in developing countries. This study recommends broader implementation supported by policy incentives, farmer training, and infrastructure investment. Future improvements could include the integration of real-time monitoring tools to optimize water delivery and expand adaptability across diverse agro-climatic conditions in the region. This adaptability ensures that smallholder farmers can confidently adopt the system in various regions of Indonesia.

Keywords: smallholder farmers; El Niño; water productivity; climate adaptation; precision agriculture

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1 Introduction

Efficient water use in agriculture has become increasingly critical under extreme climate events, as the imbalance between water availability and demand requires improved distribution strategies to safeguard food security [1]. Traditional hydraulic structures often contribute to water loss, highlighting the need for sustainable and cost-effective irrigation solutions [2]. Advances in sensor- and Internet of Things (IoT)-based irrigation have improved soil moisture management, crop yield, and quality [3]. More broadly, intelligent irrigation systems have shown potential for optimizing water use, strengthening resilience, and sustaining productivity in drought-prone regions [4, 5].

Drip irrigation, a key semi-automatic system, reduces water wastage and improves efficiency compared with traditional methods [6]. However, adoption among smallholder farmers is limited by cost barriers, insufficient technical knowledge, and poor infrastructure [7]. These challenges emphasize the importance of developing simple, affordable systems, such as timer-based drip irrigation, particularly for sustainable waxy corn cultivation in El Niño-prone regions.

The 2023 El Niño caused severe water scarcity in South Sulawesi, disrupting agriculture and food security [8]. Traditional systems fail to allocate water effectively, causing overuse in the early stages and shortages during critical periods, thereby reducing yields [9]. High-tech solutions remain inaccessible because of prohibitive costs and technical demands [10]. Thus, cost-effective, adaptive irrigation systems that improve water efficiency while remaining practical for smallholders are urgently needed [11].

Table 1 shows the sharp decline in rainfall in South Sulawesi during the 2023 El Niño, especially from July to September, when rainfall fell from 0 to 100 mm in July to 0–50 mm in August and September, before recovering in October–November (BMKG, 2023). In contrast, normal years, such as 2020 and 2022, had dry seasons of 3–4 months with rainfall of 150–300 mm, whereas La Niña in 2021 shortened the dry season to 2–3 months and increased the rainfall to 300–500 mm. El Niño 2023 extended the dry season to 4–5 months, making it the driest year in recent comparison.

To address this challenge, this study introduced a timer-based drip irrigation system for waxy corn, a drought-sensitive crop [12]. The system automates water scheduling and adjusts the volume based on plant age to maintain optimal soil moisture. Delivering water directly to the roots reduces evaporation and runoff, enhancing water-use efficiency [5]. A solenoid valve controlled by a timer minimizes labor while ensuring a reliable supply even during droughts [13]. Unlike costly AI- or sensor-based IoT systems [13, 14], this design is low-cost, scalable, and user-friendly [7]. It provides a practical balance between precision irrigation, automation, and affordability, thereby strengthening resilience and supporting sustainable water management [5, 15, 16].

Efficient irrigation scheduling is critical in drought-prone areas [17]. Conventional methods often over-irrigate during the early growth stages and ignore plant development, thereby lowering productivity [12]. Research has shown that plant age-based scheduling improves yields and water productivity in crops such as sweet corn, grapevines, rice, and wheat [12, 18, 19]. Drip irrigation increases water productivity by up to 50 %, and automation further enhances efficiency [5, 20, 21]. However, studies have largely focused on commercial crops, with waxy corn being underexplored, and advanced systems remain inaccessible to smallholders [10].

Table 1: Monthly average temperatures (2020–2023) and percentage increase in 2023 (°C).

Month	2020	2021	2022	2023	Increase in 2023 (%)
July	27.5	27.2	27.8	28.5	2.5
August	27.8	27.5	28.0	28.8	2.9
September	28.0	27.7	28.1	29.0	3.2
October	28.2	28.0	28.3	29.3	3.5
November	28.0	27.8	28.2	29.0	2.8

Source: Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG); IPCC's Global Temperature and Climate Analysis.

Water scarcity, worsened by climate change, poses persistent risks to smallholder farmers [22]. Many irrigation models rely on expensive equipment and Internet connectivity, limiting their adoption [7, 13]. Moreover, real-world testing under extreme conditions, such as El Niño, remains scarce [23]. This study addresses these gaps by developing and testing a low-cost, plant age-based drip irrigation system for waxy corn in South Sulawesi, achieving a water-use efficiency of 3.87 kg/m^3.

This study developed and evaluated a cost-effective drip irrigation system for waxy corn farming in drought-prone regions of South Sulawesi, Indonesia, particularly under the El Niño conditions. The system applies plant age-based scheduling to optimize water use, enhance crop growth and yield, and compare its performance with that of traditional irrigation methods. By integrating simple automation, water-use efficiency is improved, wastage is reduced, and smallholder farmers with limited infrastructure are supported. The findings provide empirical evidence of the effectiveness of low-cost automated irrigation, offering practical insights for sustainable water management and contributing to climate-resilient farming practices that strengthen food security in the face of climate variability.

2 Materials and methods

2.1 Resarch design

This study employed an experimental field research design to develop and evaluate a timer-based semi-automatic drip irrigation system for waxy corn cultivation in drought-prone areas of South Sulawesi, Indonesia. Unlike advanced IoT or sensor-based systems, the design operated without Internet connectivity, using a programmable timer and irrigation schedule based on plant age. The system was assembled from affordable components, including drip lines, solenoid valves, a water tank, and a timer, and was installed on a field site prepared for five planting cycles. Pre-germinated waxy corn seeds were planted in pre-wetted plots to ensure root establishment, with irrigation conducted daily at 5:30 PM, and water volumes adjusted for each growth stage.

Data collection covered the entire 65-day cropping cycle, measuring total water use, plant growth, yield per 100 plants, and operational costs. Water-use efficiency (WUE) was calculated as the total yield divided by the water applied. The economic evaluation included gross profit (revenue minus operational cost) and payback period (initial investment divided by profit per cycle). This combined agronomic and economic assessment enabled the evaluation of the system under real-world El Niño conditions, demonstrating its practicality and scalability for smallholder adoption and its contribution to climate-resilient and sustainable agriculture.

2.2 Irrigation system schematic diagram

A well-designed system schematic is essential for understanding the structure, components, and workflows of irrigation processes. Figure 1 illustrates the distribution of water from the source to the plants, highlighting key elements such as pumps, pipes, valves, and control systems to ensure efficient use and optimal crop growth. Such diagrams are valuable for planning, troubleshooting, and improving system performance, particularly in precision irrigation methods, such as drip irrigation, where accurate water application reduces waste and enhances yield. A detailed schematic also strengthens system management and promotes sustainable water use, serving as an important reference for farmers, engineers and researchers.

This study developed and tested an automated drip irrigation system to address water deficits in corn fields during the dry season. The system comprised a 1,000-L reservoir tank elevated by 1 m to generate hydrostatic pressure, connected to drip lines with emitters delivering 33.33 mL per minute (Figure 1). Flow was controlled by a programmable timer linked to a solenoid valve, operating daily at 5:30 PM, with the irrigation duration adjusted every 10 days to match plant growth until harvest on day 65. An automatic level sensor maintained water availability by activating the pump when the tank volume fell below 75 % and switching it off when full. Pre-planting procedures included pre-moistening the soil and transplanting pre-germinated seeds in the late afternoon to retain the moisture. The design prioritized simplicity and affordability, combining controlled water delivery with minimal labor demands, and routine maintenance, such as drip line cleaning, ensured reliability.

Irrigation scheduling followed a precision approach tailored to waxy corn growth stages, as detailed in the Timer Operational Time Diagram (Table 2). In the early phase (1–10 days), each plant received 0.25 L over 15 min to support germination and root establishment. Water volumes and durations were gradually increased, reaching 1.0 L per plant applied over 60 min daily during the final phase (31–65 days) to maximize nutrient uptake and yield formation. This automated, age-based schedule ensured efficient water allocation, minimized runoff and evaporation, and reduced the need for manual intervention. By aligning irrigation with crop development, the system avoided under- and over-watering, improving water-use efficiency, in line with previous findings on stage-specific irrigation benefits [5, 12]. Overall, the method demonstrated a practical, low-cost, and scalable solution for smallholder farmers in drought-prone regions, enhancing resilience to El Niño conditions [13].

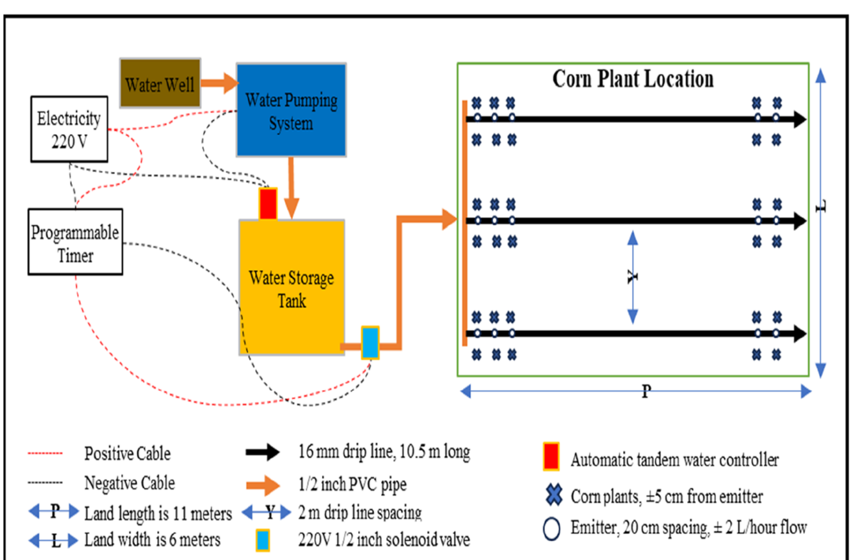

Figure 1: Operational diagram of a semi-automatic drip irrigation system for corn cultivation.

Table 2: Timer operational time diagram for semi-automatic drip irrigation system based on Waxy Corn growth stages.

Plant age (days)	Water volume per plant (L)	Daily irrigation duration(min)	Irrigation frequency per day	Timer operational time
1–10	0.25	15	1	17:00–17:15
11–20	0.50	30	1	17:00–17:30
21–30	0.75	45	1	17:00–17:45
31–65	1.00	60	1	17:00–18:00

Figure 2 presents the sequence of research activities undertaken to develop and test a low-cost, timer-based drip irrigation system for waxy corn under drought conditions induced by the El Niño phenomenon. The study began with a literature review to guide material selection and system design, followed by field installation and planting in five replicates in the experimental area. A programmable timer automatically adjusted irrigation based on plant age, and data on growth, yield, and water use were collected throughout the cycle. These data were analyzed to assess agronomic performance, water-use efficiency, and economic feasibility, leading to key findings and recommendations for the wider adoption of these practices by smallholder farmers in drought-prone areas.

2.3 Data Analysis

To evaluate the system's performance, the water-use efficiency (WUE) was calculated as the ratio of the total yield (kg) to the total water applied (m^3) over the 65-day crop cycle. Irrigation volumes increased with plant age, from 0.25 L per plant daily in the first 10 days to 1.5 L during peak growth, tapering to 1.0 L in the final stage. Each plant received 57.5 L in total (5.75 m^3 per 100 plants), producing 22.25 kg per 100 plants at harvest. The resulting WUE was 3.87 kg/m^3, which falls within the "good to outstanding" benchmark range for corn (3.0–4.0 kg/m^3). This demonstrates that the system sustained yields under drought conditions while minimizing water loss, providing strong empirical evidence of its efficiency and sustainability. The WUE was calculated as follows:

$$\text{Water use efficiency } (\%) = (\text{Water used by the plants } (\text{kg})) / \times (\text{Total water supplied } (\text{m}^3)) \times 100 \quad (1)$$

Water-use efficiency (WUE) was assessed by comparing the amount of water absorbed and utilized by the plants to the total water supplied, with higher values reflecting more effective resource use. This metric is critical for optimizing

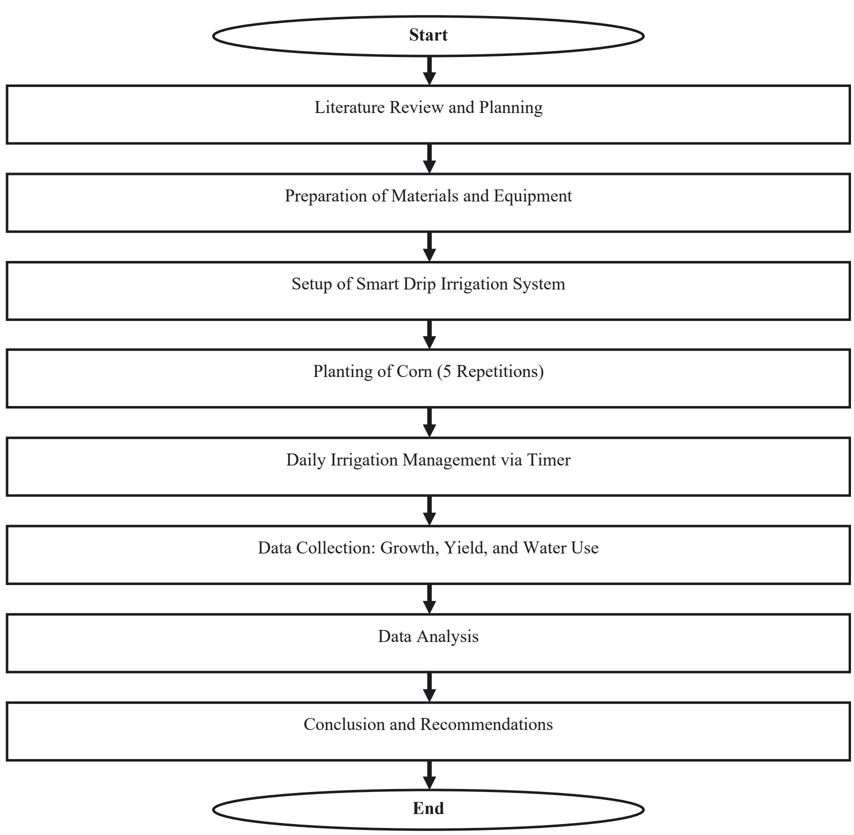

Figure 2: Research process flowchart scheme.

irrigation systems and conserving water in drought-prone regions.

The economic feasibility was evaluated through gross profit and payback period calculations. Gross profit was determined as the total revenue from crop sales minus the operational costs incurred during the five planting cycles. Revenue was calculated by multiplying the total harvest yield (kg) by the average selling price per kilogram of waxy corn. The operational costs included fertilizer, electricity, maintenance, and labor. Thus, gross profit provides a direct estimate of the financial benefits of adopting the irrigation system, highlighting its potential to improve farmer income stability in resource-constrained settings.

The payback period measures how quickly farmers can recover their initial investment, obtained by dividing the total investment costs by the gross profit generated per cycle. A short payback period indicates strong economic efficiency, making the system financially attractive to smallholder farmers. These measures demonstrate the agronomic and economic viability of the system, supporting its scalability and adoption in other drought-prone agricultural regions.

$$\text{Payback period} = (\text{Initial investment}) / (\text{Annual net cashflow}) \tag{2}$$

This formula is used to calculate the time required to recover the initial investment cost through the net cash flows generated by the investment. In other words, the payback period represents the amount of time required for the total income or savings from a project to equal the initial capital spent.

3 Results

3.1 Water use efficiency

Water-use efficiency (WUE) reflects how effectively irrigation water is utilized by plants relative to the total applied, ensuring minimal waste and maximum productivity [24–26]. Efficient systems reduce evaporation, runoff, and deep percolation while supplying crops with precise moisture at each growth stage. Precision methods, such as drip irrigation, automated scheduling, and plant age-based allocation, enhance WUE by maintaining soil moisture and nutrient uptake. Improving WUE not only boosts yields and conserves water but also strengthens resilience to drought and climate variability, making irrigation more sustainable and cost-effective, while encouraging wider adoption among farmers and practitioners.

As shown in Table 3, timer-based drip irrigation adjusted water distribution according to plant growth, starting with 0.25 L per plant per day and increasing to 1.5 L during cob formation. Over the 65-day cycle, 5.75 m^3 of water for 100 plants produced 22.25 kg of corn, resulting in a water-use efficiency (WUE) and Water Productivity (WP) of 3.87 kg/m^3. This was higher than that of conventional flooding, which achieved 3.48 kg/m^3, reflecting an efficiency gain of approximately 11 %. The drip system reduces water losses from evaporation and runoff, provides a timely supply based on crop needs, and maintains consistent yields even under drought or El Niño conditions.

According to irrigation efficiency benchmarks, the WP of 3.87 kg/m^3 falls within the “good to outstanding” range (3–4 kg/m^3), confirming that timer-based drip irrigation maximizes yield while conserving water [27–29]. Beyond higher productivity, it offers sustainability and economic advantages over flooding, which is more labor-intensive and less practical for large-scale farming. By optimizing water allocation, the system demonstrates scalability and resilience for smallholder farmers in drought-prone regions of the country.

We can compare this value with standard irrigation efficiency benchmarks for corn to assess whether it is very good, good, or poor:

- Traditional irrigation (flooding/channels): 1.0–1.8 kg/m^3
- Sprinkler irrigation: 2.0–2.5 kg/m^3
- Modern drip irrigation: 3.0–4.0 kg/m^3 (and potentially higher under optimal field conditions).

With a water productivity (WP) value of 3.87 kg/m^3, this drip irrigation system effectively maximized crop yield while minimizing water wastage, categorizing it as good to outstanding. The system’s capacity to deliver precise water quantities reduces evaporation and runoff losses, thereby ensuring optimal moisture levels in the soil. However, the integration of sensor-based or precision deficit irrigation methods could further enhance efficiency by enabling real-time monitoring and adaptive water management, thus making irrigation more precise and sustainable in water-scarce regions, such as the Mediterranean.

3.2 Fertilization and corn plant productivity

Proper fertilization is vital for plant productivity, providing macronutrients such as nitrogen, phosphorus, and potassium for growth and fruit formation, as well as micronutrients such as boron, zinc, and magnesium to support metabolism and photosynthesis [30–32]. In this study, timely fertilization promoted healthy corn growth and yields within the desired weight range, although variations in fruit size indicated differences in nutrient uptake. Refining

Table 3: Water use efficiency of corn plants until harvest.

Plant age (days)	Water volume supplied (L/plant/day)	Total water supplied (Liters/plant)	Total water supplied (m^3/100 plants)	Harvest yield (kg/100 plants)[a]	Water use efficiency (WP) (kg/m^3)[a]	Harvest yield (kg/100 plants)[b]	Water use efficiency (WP) (kg/m^3)[b]
01-Oct	0.25	2.5	0.25	–	–	–	–
Nov-20	0.50	5.0	0.50	–	–	–	–
21–30	0.75	7.5	0.75	–	–	–	–
31–40	1.00	10.0	1.00	–	–	–	–
41–50	1.25	12.5	1.25	–	–	–	–
51–60	1.50	15.0	1.50	–	–	–	–
61–65	1.00	5.0	0.50	22.25	3.87 kg/m^3	19,15	3.48 kg/m^3
Total	–	**57.5**	**5.75**	**22.25**	**3.87 kg/m^3**	**19.15**	**3.48 kg/m^3**

[a]Timer-based system; [b]Conventional flooding.

schedules or applying precision techniques could enhance nutrient distribution, improve uniformity, and maximize yield.

Table 4 outlines the fertilization schedule, consisting of two NPK Mutiara applications: 2.5 g per plant at 10–15 days and 5.0 g at 30 days, both after evening irrigation. This strategy supported growth and yield, with 50 % of corn harvested in the optimal weight range of 250–300 g, 35 % between 150 and 250 g, and 15 % below 150 g. The timing of application matched the critical growth phases, ensuring nutrient availability during the vegetative and early reproductive stages. However, the presence of smaller fruits indicates uneven nutrient uptake or environmental effects, suggesting the need for refinement. Additional fertilization before flowering or precision-based approaches could improve the uniformity and yield quality.

The fertilization schedule generally promoted healthy growth, with most harvests falling within the desired weight ranges. However, variations in fruit size indicate differences in nutrient absorption and environmental conditions. Although most plants responded well, nutrient competition and uneven distribution likely reduced uniformity. Adjusting the nutrient composition, increasing the application frequency, or integrating precision methods, such as soil moisture sensors, could enhance nutrient delivery, consistency, and overall productivity.

The fertilization schedule, shown in Figure 3, was effective in supporting crop growth, with 50 % of the harvested corn falling within the optimal weight range of 250–300 g. Another 35 % were medium-sized (150–250 g), indicating generally good nutrient response, although some variation in absorption or environmental conditions affected growth. The remaining 15 % of smaller fruits (<150 g) were likely the result of nutrient competition, uneven distribution, or stress factors.

Refining the fertilizer composition or frequency could further improve productivity. Adding micronutrients or introducing an extra application before flowering may enhance fruit uniformity, while integrating soil moisture sensors and precision techniques could improve nutrient uptake and increase the proportion of high-quality yields.

Table 4: Fertilization and corn plant productivity.

Plant age (days)	Fertilizer type	Fertilizer amount (grams/plant)	Fertilization time	Harvest weight category (%)
10–15	NPK Mutiara	2.5	After evening irrigation	–
30	NPK Mutiara	5.0	After evening irrigation	–
Harvest (65–70 days)	–	–	–	50 % (250–300 g), 35 % (150–250 g), 15 % (<150 g)

3.3 Financial analysis

The financial analysis confirmed the cost-effectiveness of the innovative drip irrigation system, demonstrating its capacity to generate profit while optimizing water use. With relatively low initial investment, the system achieved a short payback period, making it financially viable for smallholder farmers and improving their economic resilience [33]. Its high water-use efficiency supports sustainable practices by maximizing resource utilization, and the results highlight its potential to enhance productivity and profitability in drought-prone areas. Overall, the system offers a scalable solution for efficient irrigation management and provides confidence in its broader applicability.

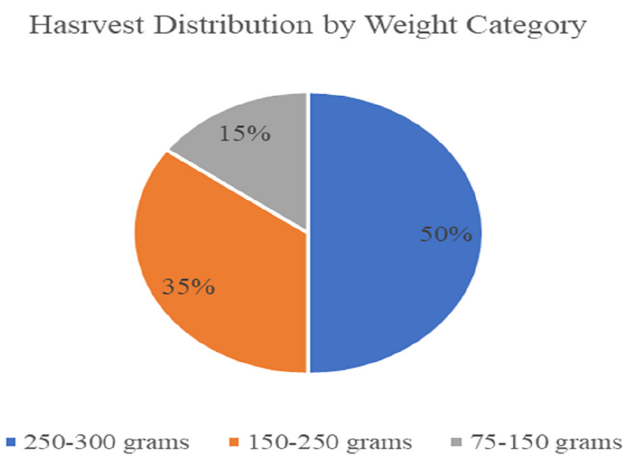

Figure 3: Fertilization and corn plant productivity.

Table 5 presents the economic analysis of the innovative drip irrigation system for waxy corn cultivation over five planting cycles. The initial investment was IDR 1,085,000, which covered essential components such as a small electric pump, 50-m drip hose, water filter, pressure regulator, valves, connectors, water tank, and installation labor. The operational costs totaled IDR 220,000, including electricity for the pump, system maintenance, labor, and fertilizer.

The system produced 111.3 kg of waxy corn across five cycles, generating a revenue of IDR 778,750 at a market price of IDR 1,750 per unit. After deducting the operational costs, the gross profit was IDR 558,750. Importantly, the analysis showed that farmers could recover their initial investment within 1.4 planting cycles, underscoring the system's financial viability for smallholders. Beyond profitability, the system also achieved a high water-use efficiency of 3.87 kg/m^3, placing it in the "good to outstanding" category of irrigation benchmarks, meaning that each cubic meter of water produced 3.87 kg of corn.

These results highlight the cost-effectiveness and sustainability of timer-based drip irrigation systems. The system not only conserves water but also provides a rapid return on investment, making it an accessible and scalable solution for smallholder farmers, particularly in drought-prone regions of the world. Furthermore, integrating real-time soil moisture monitoring or precision scheduling could enhance both economic returns and resource efficiency, reinforcing the potential of the system to strengthen resilience and support sustainable agricultural practices.

Table 5: Economic analysis over five cycles.

No	Component	Cost (IDR)	Description
1	Initial investment cost	1,085,000	Installation cost of a 10 m drip irrigation system
2	Total operational cost	220,000	Operational costs over 5 planting cycles
3	Total harvest yield	778,750	Based on the weight distribution of the harvest
4	Average selling price per unit	1,750	Market price for waxy corn
5	**Gross profit (revenue – operational cost)**	**558,750**	**Profit after operational costs**
6	Payback period (initial investment/gross profit)	1.4	Time required to recover investment
7	Water use efficiency (kg/m^3)	3.87 kg/m^3	Productivity per unit of water volume

4 Discussion

4.1 Semi-automatic irrigation systems and water management in agriculture

Automatic irrigation technologies have been widely explored as strategies to improve water-use efficiency in agriculture, especially under climate change and drought pressure [34–36]. Sensor-based irrigation systems have demonstrated significant reductions in water wastage compared to conventional flooding [5, 16]. Studies have shown that integrating soil moisture sensors and real-time weather data can reduce water use by 40–50 % while sustaining crop yields. However, these high-tech systems require substantial investment and technical expertise, limiting their suitability for smallholder farmers with limited resources [37, 38].

To address these barriers, this study introduced a low-cost, timer-based, semi-automatic irrigation system designed to function without Internet connectivity or complex automation [39]. Unlike AI-driven irrigation models, it employs a plant age-based schedule, allowing efficient water allocation at different growth stages with minimal operational cost [40]. This design reduces farmers' dependence on advanced technologies while enhancing water-use efficiency, making it particularly relevant in drought-prone areas [41]. Its affordability and simplicity set it apart from high-tech solutions [42] and offer potential economic benefits to policymakers.

Plant age-based irrigation scheduling has been studied in rice and wheat [12, 18], little attention has been given to waxy corn, which is highly sensitive to water stress. Our findings demonstrate that structured irrigation significantly improved waxy corn productivity, achieving a water-use efficiency (WUE) of 3.87 kg/m^3, which is consistent with the "good to outstanding" benchmark [43]. This highlights the value of age-based scheduling as a viable strategy for managing water in drought-sensitive crops.

A key distinction of this study is its reliance on structured scheduling, rather than soil moisture sensors. Although sensors provide real-time water management, their cost and maintenance requirements often restrict their adoption [14]. By applying a predefined irrigation schedule aligned with crop growth stages, our model reduced excess watering in the early development stage and ensured a sufficient supply during critical phases. This balance between efficiency and accessibility offers a practical alternative to technologically intensive approaches.

Many previous studies have tested irrigation under controlled environments [44, 45], raising questions about their field applicability. In contrast, our study validated the performance of the models under real-world El Niño-induced drought conditions in South Sulawesi. The prolonged dry season and irregular rainfall in 2023 provided an opportunity to evaluate the resilience of the system. The results showed consistent yields despite severe water shortages, underscoring the potential of this approach as a climate-resilient solution for smallholder farmers.

By bridging the gap between advanced automation and farmer-friendly design, this study contributes three novel elements: (1) demonstration of structured irrigation scheduling for waxy corn, a crop rarely studied under climate stress; (2) validation of system performance under extreme drought conditions; and (3) provision of a low-cost, scalable alternative to high-tech irrigation. These contributions address gaps in the literature, where most studies have emphasized IoT-based precision models [13, 46] or focused only on major staples such as rice and wheat [47].

These findings highlight that timer-based drip irrigation conserves water, maintains yields, and provides a practical and affordable pathway for smallholder farmers. With water-use efficiency in the "good to outstanding" range, the system demonstrates that structured, age-specific irrigation can achieve sustainability goals without requiring costly infrastructure development. By validating the effectiveness of this model under El Niño conditions, this study reinforces the importance of adaptable, low-cost water management systems. These insights strengthen the evidence base for promoting timer-based drip irrigation as a scalable approach for sustainable agriculture in drought-prone regions of the world.

4.2 Plant age-based irrigation management

Plant age-based irrigation management has emerged as an effective strategy for optimizing water-use efficiency while maintaining the crop productivity. Studies on wheat and rice have shown that adjusting irrigation according to growth stages can reduce water use by 20–30 % without compromising yields [5, 12]. However, research has largely focused on staple crops, leaving a gap in knowledge regarding high-value crops such as waxy corn, which is particularly vulnerable to drought stress and requires precise water management.

Sensor-based irrigation systems have also proven effective in reducing water waste [14, 48, 49]; however, their high cost, maintenance needs, and reliance on connectivity limit their adoption among smallholder farmers. As noted by Pandey* and Agarwal [50], financial and technical barriers remain the major obstacles. To address these limitations, our study introduced a low-cost, timer-based irrigation model that applies structured schedules without requiring sensors or Internet connectivity. This approach provides farmers with a simple, affordable, and scalable alternative that aligns with resource constraints.

Aligning irrigation with crop physiology is critical for water-sensitive plants [18, 19]. However, few studies have examined stage-based irrigation for waxy corn. Our study bridges this gap by providing empirical evidence that adjusting water allocation across developmental stages can improve yield and water-use efficiency. The system achieved a WUE of 3.87 kg/m^3, placing it within the "good to outstanding" benchmark and demonstrating the practical value of age-specific irrigation for drought-sensitive crops.

Another distinction is that prior studies have often tested irrigation under controlled greenhouse or experimental conditions [20, 21, 51]. limiting the understanding of field performance. In contrast, our study validated the model under a real-world El Niño-induced drought in South Sulawesi. The extended dry season and erratic rainfall provided a unique opportunity to test the resilience of the system. The results showed consistent yields despite severe water shortages, confirming the adaptability of structured irrigation schedules under extreme climate stress.

Previous studies have also emphasized high-tech, AI-driven models [13, 52, 53]. Although effective, these systems remain inaccessible to smallholders because of their cost and technical complexity. Our findings reinforce that a predefined, growth stage-based schedule can deliver similar efficiency benefits without the need for expensive technologies [14, 54]. This practical approach ensures efficient water delivery during the early development and critical reproductive phases, thereby reducing waste and improving productivity.

Finally, few studies have validated irrigation strategies under drought stress in real-world settings [55, 56]. Our research contributes unique evidence from El Niño conditions, showing that timer-based irrigation not only sustains crop yields but also strengthens climate resilience.

By addressing these gaps, this study demonstrates that low-cost, plant age-based irrigation can provide scalable and climate-resilient water management solutions. This approach offers smallholder farmers an accessible pathway to improve productivity, conserve resources and adapt to increasing climate variability.

4.3 Challenges in adopting semi-automatic irrigation for smallholder farmers

The adoption of automatic irrigation technologies has been widely promoted to enhance water-use efficiency and improve crop productivity in water-scarce regions. Sensor-based systems have been shown to significantly reduce water wastage while sustaining or increasing yields [5, 57–59]. However, despite these advantages, smallholder farmers often face substantial barriers that limit their adoption.

A major obstacle is the high initial investment required for IoT-based and AI-driven irrigation systems, which rely on soil moisture sensors, automated controllers, and data processing software [13, 60–62]. Such costs render these technologies inaccessible to farmers in developing countries. Our study addresses this challenge by introducing a low-cost, timer-based irrigation model that eliminates the need for expensive equipment and provides a financially viable alternative for smallholders.

Another challenge is the lack of technical expertise required to operate and maintain advanced irrigation systems. Many smallholder farmers are unfamiliar with sensor-based models, and their adoption is often hindered by insufficient extension services and training programs [14, 63, 64]. Our model addresses this issue by using a structured irrigation schedule based on plant age that requires minimal technical knowledge. This design ensures that farmers can efficiently manage water allocation without relying on real-time data monitoring, thereby increasing accessibility and usability.

Infrastructure limitations further restrict this adoption. Many rural farmers face unreliable electricity and poor Internet connectivity, making cloud-based or IoT-dependent systems impractical [10, 65]. Existing automatic models often depend on continuous data transmission, which is unfeasible in remote areas [12, 66]. Our system overcomes this barrier by using a simple automated timer that operates independently of Internet connectivity. This ensures reliable and consistent water delivery, making the system particularly suitable for resource-constrained environments such as arid regions.

While precision irrigation research has highlighted the benefits of advanced technologies, relatively few studies have focused on cost-effective alternatives for smallholder farmers [67, 68]. Most work has emphasized high-tech solutions that demand significant financial and technical inputs [5, 69]. Our study fills this gap by demonstrating that a practical, affordable, timer-based model can achieve high efficiency without relying on sensors or cloud platforms.

Another gap lies in the structured irrigation scheduling for smallholder farmers. Previous research has mainly focused on real-time soil moisture monitoring, whereas few studies have tested predefined irrigation schedules aligned with crop growth stages [14, 70, 71]. Our findings provide empirical evidence that stage-based scheduling achieves efficiency comparable to that of sensor-based systems, offering an accessible alternative for smallholders.

Finally, although many studies have tested irrigation systems under controlled or commercial farm conditions, limited research has validated their performance in extreme climates [34, 72]. Our study is unique in demonstrating the effectiveness of the system under El Niño-induced drought in South Sulawesi, where it sustained yields despite prolonged water scarcity. This real-world validation highlights the resilience and scalability of timer-based irrigation as a practical solution for smallholder farmers facing increasing climate variability in the future.

4.4 Economic impact and sustainability

The economic impact of automatic irrigation systems has been widely studied, particularly in terms of water-use efficiency and cost savings. Research has shown that such systems can reduce water consumption by 30–50 %, resulting in significant savings for farmers [5, 73]. Sensor-based irrigation has also been shown to increase yields by up to 20 % while lowering costs, making it attractive for commercial use [13]. However, most studies have focused on large-scale agriculture, with limited evidence on the economic feasibility of semi-automatic systems for smallholder farmers.

High upfront costs remain a critical barrier for smallholders, as automatic irrigation often requires investments in sensors, automation, and cloud platforms [10, 74]. Although the long-term benefits are well documented, the initial investment limits adoption in developing countries [14, 38, 75]. Our study addresses this by analyzing a low-cost, timer-based irrigation system that avoids the use of expensive technology. With a payback period of only 1.4 planting cycles, the results highlight the financial viability of structured irrigation by smallholders.

Beyond short-term profits, few studies have examined the long-term sustainability impacts of automatic irrigation systems [73, 76]. Water conservation is essential for agricultural sustainability in the face of increasing climate variability [12, 77]. However, most research emphasizes high-tech models that are inaccessible to resource-poor farmers [78, 79]. Our findings demonstrate that growth-stage-based semi-automatic irrigation can improve both economic outcomes and long-term sustainability without requiring advanced technology.

The existing literature also underexplores how low-cost irrigation strengthens the economic resilience of smallholders. Most studies emphasize commercial-scale profitability, overlooking the constraints faced by resource-limited farmers [80, 81]. Our study contributes to the literature by showing how affordable irrigation models minimize financial risks while delivering consistent benefits.

Sustainability assessments of smallholder-focused irrigation are scarce. Although efficient water use reduces environmental degradation [14, 82], few studies have analyzed the cumulative impacts of structured irrigation schedules [72, 83]. Our results provide empirical evidence that a predefined schedule optimizes water use, reduces over-irrigation, and enhances soil conservation, thereby strengthening long-term sustainability.

Finally, although high-tech irrigation is often linked to climate adaptation, the need for low-cost climate-resilient systems for smallholders is frequently overlooked [13, 84]. By validating performance under El Niño-induced drought, our study shows that structured irrigation can support both economic and environmental resilience, offering a viable and scalable solution for water-scarce regions in the future.

4.5 Relevance to the El Niño phenomenon and climate resilience

The 2023 El Niño had a severe impact on agriculture, particularly in drought-prone South Sulawesi [85]. Rainfall between July and September dropped to only 0–100 mm, far below previous years, extending the dry season to 4–5 months and making 2023 one of the driest periods in decades (BMKG 2023). This drastic decline in rainfall triggered water shortages, which reduced agricultural productivity and threatened food security (Table 1).

The semi-automatic drip irrigation system developed in this study directly addresses these challenges. With a water-use efficiency (WUE) of 3.87 kg/m^3, the system optimizes water allocation by minimizing evaporation, runoff, and deep percolation, consistent with findings that drip irrigation can improve efficiency by 40–50 % compared with traditional methods [5, 59]. An innovative feature of this system is its plant age-based scheduling: 0.25 L/day was supplied during early growth (1–10 days), increasing to 1.5 L/day in the final phase (51–60 days). This structured approach ensured optimal growth of waxy corn and maintained its productivity under extreme drought conditions.

Another key advantage is its affordability. With an initial investment of IDR 1,085,000 and a payback period of only 1.4 planting cycles, the system is financially viable for smallholder farmers, who are often excluded from high-cost irrigation technologies [10, 39]. Its simplicity and low operational requirements make it particularly suitable for resource-limited regions, enhancing agricultural resilience to climate variability.

The system also contributes to food security, which is a growing concern under climate change [86–88]. Even during severe drought, it produced waxy corn with stable yields, with 50 % of the harvests falling in the optimal 250–300 g weight range. By combining high water efficiency with reliable productivity, the system supports both sustainable food production and the conservation of scarce water resources.

In addition to the yield benefits, the system has environmental advantages. Efficient water delivery reduces the agricultural footprint, whereas stage-specific application of NPK fertilizer minimizes the risks of nutrient runoff and pollution, which are common problems in conventional irrigation [89]. These features strengthen the role of biochar in climate change mitigation.

Overall, the semi-automatic drip irrigation system offers a practical, low-cost, and sustainable response to the El Niño and broader climate challenges. By integrating timer-based automation with age-based water allocation, it provides smallholders with a scalable solution to water crises and food insecurity issues. Future improvements could incorporate real-time sensors and deficit irrigation techniques to enable adaptive water management to meet increasingly complex climate demands.

4.6 Water-use efficiency in semi-automatic irrigation systems

Water-use efficiency (WUE) is central to sustainable agricultural productivity and effective irrigation management [90, 91]. Automatic irrigation technologies, particularly sensor-based and precision systems, have been shown to significantly reduce water loss and improve crop yields [5, 92]. For example, AI-driven irrigation can lower water use by 40–50 % compared with conventional flooding while maintaining crop yields [93]. Despite these advantages, their high investment and technical requirements limit their adoption by smallholder farmers in developing countries.

Our study addresses this gap by introducing a low-cost, timer-based irrigation system that ensures efficient water distribution without the use of soil moisture sensors. Unlike sensor-based models, which continuously adjust moisture levels, our system uses a predefined schedule aligned with plant growth stages, reducing excess application while maintaining optimal hydration. This structured scheduling approach has proven effective for crops such as wheat and rice [12], but its application to high-value crops such as waxy corn under severe drought conditions has rarely been explored [9].

Drip irrigation is widely recognized for improving water productivity by directly supplying water to plant roots, thereby reducing evaporation and runoff [6, 94]. However, most research has focused on commercial farms [1], with limited attention to low-cost models suitable for smallholders [39, 95]. Our study contributes to the field by designing and field-testing an affordable, timer-based drip system adapted to smallholder contexts in drought-prone regions.

Although automatic irrigation has been extensively studied, few studies have examined structured irrigation scheduling accessible to farmers without advanced technologies [10, 68, 70]. Most models emphasize sensor-based automation, which remains financially and technically out of reach for resource-constrained farmers [96, 97]. Our findings show that a timer-controlled system can deliver a comparable WUE without external connectivity or complex equipment.

Another important contribution is the real-world validation. Previous studies have often tested irrigation under controlled conditions [14], with limited analysis of system performance under drought stress [98]. By implementing our system during the El Niño-induced drought in South Sulawesi, we provide practical evidence of its effectiveness as a climate-adaptation strategy. The system achieved a WUE of 3.87 kg/m^3, which is within the “good to outstanding” benchmark for irrigation efficiency.

While prior studies have largely focused on staple crops, limited research has assessed structured irrigation for waxy corn [12, 99]. Our results demonstrate that plant age-based irrigation not only improves water efficiency but also supports yield stability in waxy corn, reinforcing its potential as a scalable solution for smallholder farmers in water-scarce environments.

4.7 Research limitations and future directions

This study demonstrates the potential of semi-automatic irrigation systems to enhance water efficiency and crop productivity; however, several limitations must be acknowledged. The absence of real-time soil moisture monitoring reduces the precision of water delivery, as the system relies solely on a plant age-based schedule and does not account for field-level variations in the moisture content. Furthermore, the research was conducted within a specific environmental setting, meaning that its applicability under different soil types, rainfall regimes, and water availability requires further validation. These contextual factors may influence the system’s performance across regions. Therefore, future research should integrate soil moisture sensors or IoT-based technologies to enable real-time adjustments and test the system across diverse agroecological zones to evaluate its scalability and resilience. In conclusion, although the system provides a practical, efficient, and affordable solution for smallholder farmers, continued innovation and cross-location testing are essential to strengthen its adaptability and ensure its long-term sustainability.

5 Conclusions and policy implication

This study demonstrates the effectiveness of a low-cost, timer-based, semi-automatic drip irrigation system for waxy corn cultivation under El Niño-induced drought conditions in South Sulawesi, Indonesia. By following a plant age-based schedule, the system achieved a water-use efficiency of 3.87 kg/m^3, categorized as “good to outstanding” while maintaining stable yields and reducing labor demands. Economically, its short payback period of only 1.4 planting cycles highlights its affordability and practicality for smallholder farmers in the region. Beyond the farm level, the system contributes to climate adaptation by improving water productivity, reducing drought vulnerability, and supporting the food security. These findings underscore that structured irrigation scheduling can serve as a scalable and climate-smart alternative to costly sensor-based technologies. Policy support through targeted subsidies, farmer training, and integration into climate adaptation programs will be critical for wider adoption, ensuring sustainable water management, enhancing resilience, and improving livelihoods in drought-prone agricultural regions.

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Conflict of interest: The authors declare that they have no known financial or non-financial conflicts of interest related to the subject matter or materials discussed in this manuscript. They affirm that they have no affiliation with any organization or entity with a financial interest in the outcomes of this research. Additionally, the authors confirm that no personal circumstances or relationships could be perceived as unduly influencing the interpretation or presentation of the results.

Data availability statement: Raw data supporting the findings of this study are available from the authors upon reasonable request. Because the dataset reflects specific local conditions and may have limited generalizability beyond its original context, data access is managed on a case-by-case basis to ensure appropriate use and interpretation.

Ethical approval: This study involved a farm-based experimental design with no participation of human or animal subjects. According to the guidelines of Hasanuddin University, ethical approval was not required for this study. All experimental procedures followed institutional policies and national regulations concerning research on agricultural practices and environmental safety.

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