Research on World Agricultural Economy
https://journals.nasspublishing.com/index.php/rwae

ARTICLE

Enhancing Onion (*Allium cepa*) Yields: Integrating Precision Irrigation with Real-Time Soil Moisture and Mulching Strategies for Optimum Productivity

Jean Nzuma [1*], ***Abigirl Matsaure*** [2], ***Godwin Mtetwa*** [2], ***Liana-Lisa Sakwa*** [1], ***Linda Munyaradzi*** [1], ***Vimbai Samukange*** [1], ***Leonard Madzingaidzo*** [1]

[1] *Biotechnology Research Institute, Scientific and Industrial Research and Development Centre (SIRDC), Harare P.O. Box 6640, Zimbabwe*
[2] *Chiredzi Research Station, Chiredzi P.O. Box 97, Zimbabwe*

ABSTRACT

This study investigated the effects of various mulching conditions and irrigation techniques on the yield of Texas Grano onions (*Allium cepa*), a key crop for smallholder farmers in Zimbabwe. The primary objective was to identify optimal practices that enhance productivity, water productivity (WP), and water use efficiency (WUE) in onion cultivation. Four mulching treatments were evaluated: control (no mulch), maize residue, soybean trash, and grass. Concurrently, three irrigation methods were assessed: drip irrigation with Chameleon sensors for real-time moisture monitoring, drip irrigation without sensors, and traditional furrow irrigation. A 3 × 4 factorial split-plot design was employed within a randomized complete block design (RCBD) framework, with three replications. The main plots were allocated for irrigation techniques, while the sub-plots comprised the mulching treatments, including a control. A comprehensive cost-benefit analysis evaluated the economic viability of each treatment. Results indicated that combining drip irrigation with Chameleon sensors and maize residue mulch significantly increased both yields and economic returns. These findings highlight the advantages of adopting precision agricultural prac-

*CORRESPONDING AUTHOR:
Jean Nzuma, Biotechnology Research Institute, Scientific and Industrial Research and Development Centre (SIRDC), Harare P.O. Box 6640, Zimbabwe; Email: jknzuma@yahoo.com or jnzuma@sirdc.ac.zw

ARTICLE INFO
Received: 17 September 2024 | Revised: 31 October 2024 | Accepted: 1 November 2024 | Published Online: 9 January 2025
DOI: https://doi.org/10.36956/rwae.v6i1.1334

CITATION
Nzuma, J., Matsaure, A., Mtetwa, G., et al., 2025. Enhancing Onion (*Allium cepa*) Yields: Integrating Precision Irrigation with Real-Time Soil Moisture and Mulching Strategies for Optimum Productivity. Research on World Agricultural Economy. 6(1): 172–186. DOI: https://doi.org/10.36956/rwae.v6i1.1334

tices, particularly real-time moisture monitoring, to improve WP and WUE while enhancing resource utilization, thereby increasing system resilience. To fully harness these benefits, farmers should be capacitated and empowered through training on precision irrigation and mulching techniques via demonstration plots and farmer field schools (FFS). Establishing innovation hubs within irrigation schemes is recommended to foster resource sharing and technology adoption, improving productivity and market access for high-value crops. Policymakers must prioritize support for these initiatives to promote sustainable agricultural practices.

Keywords: Irrigation Techniques; Mulching; Moisture Monitoring; Productivity; Economic Viability; Smallholder Farmers; Sustainability; Resource Use

1. Introduction

Precision irrigation technologies have been extensively researched and widely adopted in many developed countries to improve water-use efficiency and crop yields. The use of drip irrigation systems equipped with soil moisture sensors has significantly increased yields while reducing water consumption by as much as 40% [1–3]. Precision agriculture technologies, such as real-time irrigation scheduling and soil moisture monitoring with Chameleon sensors, are revolutionizing water management in farming by optimizing water use. These sensors ensure water is delivered only when and where it is needed, effectively preventing losses due to evaporation and runoff. By providing real-time information on soil moisture levels, Chameleon sensors enable farmers to make informed irrigation decisions, leading to improved water productivity. This targeted approach not only conserves water but also enhances crop health and yields, making it a sustainable solution for modern agriculture [4–9].

In Africa, the adoption of precision irrigation technologies has been slower due to financial and knowledge constraints. Despite these barriers, studies conducted in various countries show promising results when precision irrigation is applied. For instance, drip irrigation combined with soil moisture monitoring has shown significant increases in crop yields compared to traditional methods [1, 3]. Similarly, farmers using advanced irrigation systems experienced substantial water savings while maintaining high yields [9–11]. These findings underscore the potential for widespread benefits if precision irrigation technologies are adopted more broadly across the continent.

Mulching is another practice that has shown significant improvements in crop yields. It functions by conserving soil moisture, moderating soil temperature, and inhibiting weed growth. Studies indicate that organic mulches like maize straw and soybean residue improve water use efficiency and boost crop productivity. However, relatively few studies have examined the combined effects of mulching and precision irrigation for onion production, particularly in Africa. Maize residue has been highlighted as a particularly effective mulch due to its high carbon-to-nitrogen ratio, which provides long-lasting benefits in terms of moisture retention and soil fertility [8, 12–14].

The interaction between irrigation methods and mulching types can also affect nutrient cycling and soil structure. For example, studies have shown that organic mulches, when used in combination with drip irrigation, improve nutrient availability in the soil, leading to enhanced crop growth and yield [9, 14]. Similarly, the use of soybean trash and maize residue has been shown to improve soil aeration and reduce soil compaction, factors critical for optimal root development in onions [4, 9].

Another key area of research is the impact of mulching on water-use efficiency. Studies have found that maize residue mulch reduces the amount of water needed for irrigation by improving soil moisture retention. This result is particularly important for regions facing water scarcity. In a similar study, it was observed that mulching reduced water evaporation by up to 30%, leading to higher yields with less water. These results are consistent with findings from studies conducted in India and sub-Saharan Africa, where mulching helped to mitigate the effects of drought on crop production [5, 12, 14].

Research conducted in Zimbabwe, while limited, suggests that smallholder farmers can benefit from the adoption of mulching and improved irrigation practices. One study found that the application of maize residue mulch on maize crops improved yields by 20% in semi-arid regions [12]. In light of these considerations, enhancing agricultural water productivity through precision irrigation is essential for addressing global food security challenges. Water productivity refers to the amount of crop yield produced per unit of water used. This makes it an important indicator that reflects both efficiency and sustainability in agricultural practices [5, 8]. By integrating advanced irrigation technologies with effective mulching strategies, farmers can optimize their resource use while maximizing crop outputs [14]. Nonetheless, there remains a gap in thorough research specifically examining the synergy between drip irrigation and mulching for high-value crops such as onions.

Overall, the literature suggests that integrating precision irrigation with mulching could lead to significant improvements in water use efficiency and crop yields. While most studies have focused on irrigation or mulching independently, this study aims to fill a critical gap by exploring the interaction between these two factors in the production of Texas Grano onions in Zimbabwe. The findings of this research will contribute not only to the academic body of knowledge but also provide practical recommendations for smallholder farmers seeking to enhance productivity in areas with limited water resources [1–3, 7–9, 14, 15].

2. Materials and Methods

2.1. Study Site

The study was conducted over the winter seasons of 2022 and 2023 at Chiredzi Research Station in Zimbabwe's Natural Region IV, an area known for low rainfall and high temperatures, making it ideal for water-efficient agriculture trials. During the winter seasons, rainfall was scarce, with 2023 receiving slightly lower amounts in May, June, and July compared to 2022, while average minimum and maximum temperatures slightly increased in 2023 (13 °C to 31 °C) relative to 2022 (12 °C to 30 °C) (**Table 1**). Soils at the site were classified as clay loam with a pH ($CaCl_2$) of 6.5, organic matter content of 2.2%, nitrogen (N) at 0.18%, phosphorus (P) at 15 mg kg–1, and potassium (K) at 0.48 meq $100g^{-1}$ [16, 17].

2.2. Experimental Design

A 3 × 4 factorial split-plot design within a randomized complete block design (RCBD) was employed to examine the effects of three irrigation methods and four mulching treatments on Texas Grano onion yield. Each treatment combination was replicated three times on 6 m^2 plots, with 7 cm spacing between plants and 20 cm between rows, resulting in a planting density of approximately 71,429 plants per hectare. This factorial approach allowed for detailed examination of both individual and interactive effects of irrigation and mulching on onion yield (**Table 2**).

2.3. Irrigation and Soil Moisture Management

Texas Grano onion seedlings were transplanted at a density of approximately 71,429 plants per hectare, with in-row and inter-row spacing of 7 cm and 20 cm, respectively. To maintain consistent moisture levels, furrow irrigation was applied manually. For the drip irrigation system, two distinct approaches were implemented:

1. Fixed Irrigation Schedule: This method was used for the system without sensors, where irrigation occurred on a predetermined schedule.
2. Real-Time Adjustments: The system equipped with Chameleon soil moisture sensors allowed for real-time adjustments based on feedback from the sensors.

These Chameleon sensors monitor moisture levels in the root zone and utilize color indicators (blue, green, and red) to convey soil suction thresholds:

- Green: Signifies optimal moisture levels, corresponding to suction readings between 20 and 50 kPa.
- Blue: Indicates sufficient moisture, with suction readings below 20 kPa.
- Red: Signals potential water stress, with suction readings above 50 kPa, prompting timely irrigation to prevent yield losses.

Table 1. 2022 and 2023 rainfall and temperature data (April to July) at the study site.

Month	Total Rainfall (mm)	Min Temperature (°C)	Max Temperature (°C)
April	50.0 (29.1)	15.0 (19.0)	32.0 (31.0)
May	40.0 (23.6)	16.0 (20.0)	30.0 (30.0)
June	20.0 (5.8)	17.0 (21.0)	28.0 (29.0)
July	10.0 (0.0)	18.0 (22.0)	27.0 (28.0)

Note: Values in parentheses represent data for the winter season of 2023, while those without parentheses are from 2022.
Source: [16].

Table 2. Design and treatments of the study.

Factor	Treatment	Description
Irrigation systems	Furrow	Manual irrigation using standard buckets.
	Drip irrigation with soil moisture monitoring	Drip irrigation system equipped with Chameleon sensors for real-time soil moisture data
	Drip irrigation without sensors	Conventional drip irrigation system delivering water directly to the base of the plants
Mulch conditions	Control (no mulch)	No mulch applied.
	Maize straw	Dried maize straw was applied as mulch.
	Soya bean trash	Dried soya bean trash was applied as mulch.
	Grass	Dried cut grass

Note: Grass species used as mulch was Bermudagrass (Cynodon dactylon).

By providing real-time feedback, these color-coded sensors ensure efficient irrigation tailored to the crop's soil moisture needs, which is crucial for optimizing water use in arid climates [7, 10, 11, 15].

2.4. Water Productivity and Water Use Efficiency Calculations

To assess the effectiveness of various irrigation methods in onion cultivation, calculations for Water Productivity (WP) and Water Use Efficiency (WUE) were conducted [10]. To calculate the metrics, the following formulas were employed:

- Water Productivity (WP) = Yield (t ha^{-1}) / Total Water Applied (m^3 ha^{-1})
- Water Use Efficiency (WUE) = Yield (t ha^{-1}) / Total Water Used (m^3 ha^{-1})

In this context, Total Water Applied included both irrigation and effective rainfall received during the growing season. The calculations were performed for each treatment to provide insights into how different irrigation practices impacted water utilization [10].

2.5. Mulch Application and Management

The mulch materials were uniformly applied to each subplot at the rate of 5 tons per hectare, initially covering the soil surface completely around the plants to a thickness of approximately 5 cm. No additional mulch was applied after the initial application, allowing for the natural decomposition process to take place and simulate the real-life practices of smallholder farmers. The effects of mulching on soil moisture content in the mulched and non-mulched plots were monitored using Chameleon sensors to compare the ability of each mulch type to retain soil moisture and to guide irrigation scheduling.

2.6. Soil and Plant Management

Texas Grano onion seedlings were transplanted at the 4-leaf stage, and standard fertilizer practices were applied uniformly across all plots to prevent fertility differences from influencing the results. A compound fertilizer (NPK 5:15:12) was applied during planting at a rate of 600 kg per hectare. This was followed by a top dressing of ammonium nitrate at a rate of 100 kg per hectare four weeks after transplanting. Regular pest and disease control measures were implemented throughout the season, including the use of registered pesticides and fungicides, to ensure that pest pressure did not confound the experimental results. Weeds were manually removed from all plots.

2.7. Data Collection

During the study period, irrigation frequency was monitored across all treatments. After harvesting, a comprehensive evaluation of both fresh and dry biomass was conducted to assess crop productivity. This evaluation was essential for determining the effectiveness of the various treatments implemented throughout the growing season. To accurately quantify onion production, key yield components were measured, including average bulb weight, total yield, and marketable yield. A total of twenty pre-tagged plants from each plot were sampled to ensure that the data collected was representative of the entire plot. This method allowed for a more precise analysis of how different irrigation and mulching treatments affected onion growth. The marketable bulb yield was defined as the total weight of disease-free, undamaged bulbs weighing more than 21 grams. This criterion ensured that only high-quality produce was included in yield calculations, which is crucial for assessing the economic viability of the onion crop.

2.8. Statistical Analysis

The gathered data were analysed using analysis of variance (ANOVA) to assess the effects of various irrigation methods, mulching types, and their interactions on key factors like yield, water-use efficiency, and soil moisture retention. The statistical software SPSS 12.0 facilitated robust interpretations of the results. Mean comparisons among treatment groups were conducted using least significant differences (LSD) at the 5% significance level to identify statistically significant treatment combinations. Additionally, correlation analysis was performed to explore relationships between critical variables, such as bulb weight and total yield, aiming to reveal significant associations that could inform future agricultural practices and improve onion production understanding.

3. Results

3.1. Irrigation Frequency across Various Irrigation Techniques

The results of the study revealed distinct irrigation frequencies across three irrigation techniques, as summarized in **Table 3**. Each technique exhibited the following irrigation intervals:

- Drip Irrigation with Chameleon Sensors: Operated on an irrigation frequency of every 2 to 3 days. The integration of Chameleon sensors allowed for real-time soil moisture monitoring, enabling precise and frequent watering. This approach ensured consistent soil moisture levels, optimizing conditions for onion growth.
- Drip Irrigation without Sensors: Followed a fixed schedule, with irrigation occurring every 4 to 5 days. While this method is more efficient than traditional practices, it lacks the adaptability to respond to changing soil moisture conditions.
- Traditional Furrow Irrigation: Required irrigation every 5 to 7 days, depending on rainfall and evaporation rates. Although it involved larger volumes of water applied less frequently, this method was less efficient, leading to higher evaporation losses and less consistent soil moisture levels.

Table 3. Irrigation frequency among various irrigation techniques.

Irrigation Technique	Irrigation Frequency (Days)
Drip irrigation with chameleon sensors	Every 2 to 3 days
Drip irrigation without sensors	Every 4 to 5 days
Traditional furrow irrigation	Every 5 to 7 days

3.2. Mean Bulb Weight of Onions under Varying Irrigation and Mulch Treatments

The mean bulb weight of onions was significantly influenced by the irrigation methods and mulch types employed in the study. The results for mean bulb weight (in grams) for both the 2022 and 2023 growing seasons are summarized in **Table 4**.

In the Furrow Irrigation treatment, the mean bulb weight was observed to be 58.4 g in 2022 and increased to 60.6 g in 2023, indicating a consistent performance across the years. However, these values were significantly lower than those observed with the other irrigation methods.

For Drip Irrigation with Sensors, a substantial increase in mean bulb weight was recorded, with values of 99.4 g in 2022 and 102.0 g in 2023. This method yielded the highest bulb weights across both seasons, demonstrating its effectiveness in enhancing onion growth.

In the Drip Irrigation without Sensors treatment, mean bulb weights were also notable, with averages of 84.9 g in 2022 and 86.0 g in 2023. Although these figures were lower than those from the sensor-assisted drip irrigation, they still exceeded the weights obtained under the furrow irrigation method.

The mean bulb weights for onions grown with various mulch types were also evaluated. Under maize residue, mean bulb weights were 96.7 g in 2022 and 99.7 g in 2023, showing a slight improvement in the second year. The Soya Bean Trash treatment yielded average bulb weights of 85.6 g in 2022 and 87.6 g in 2023, while the Grass mulch resulted in mean bulb weights of 74.9 g in 2022 and 76.4 g in 2023.

Table 4. Mean bulb weight (g) for different irrigation methods and mulch types (2022 and 2023).

Irrigation Method	**Control**		**Maize Residue**		**Soya Bean Trash**		**Grass**		**Mean Bulb Weight**		**CV%**	**SE**	**LSD**
	(2022)	**(2023)**	**(2022)**	**(2023)**	**(2022)**	**(2023)**	**(2022)**	**(2023)**	**(2022)**	**(2023)**			
Furrow irrigation	50.5^{a}	52.3^{a}	70.2^{b}	73.8^{b}	58.3^{c}	60.1^{c}	54.5^{c}	56.2^{c}	58.4^{c}	60.6^{c}	10%	1.82	3.65
Drip with sensors	78.5^{d}	80.1^{d}	120.3^{e}	123.5^{e}	108.2^{d}	110.4^{d}	90.6^{d}	93.8^{d}	99.4^{d}	102.0^{d}	14%	2.56	5.12
Drip without sensors	70.2^{c}	72.1^{c}	99.5^{d}	102.0^{d}	90.3^{c}	92.5^{c}	79.5^{c}	81.2^{c}	84.9^{c}	86.0^{c}	18%	3.28	6.56
Mean bulb weight	66.4	68.1	96.7	99.7	85.6	87.6	74.9	76.4	81.6	83.0	20%	3.65	7.30

Note: Values in parentheses represent the average bulb weight for the 2023 winter season. The mean separation letters (a, b, c, d, e) indicate groups that are statistically similar based on the analysis of variance (ANOVA) conducted on the data from both years (2022 and 2023). For instance, treatments sharing the same letter are not significantly different from each other, highlighting comparable performance in bulb weight across the two seasons. This ensures that any observed differences in average bulb weight can be attributed to the irrigation methods and mulch types rather than seasonal variability.

3.3. Interaction Effects on Yield and Marketable Yield

Results suggest significant interaction effects between irrigation methods and mulch types on yield and marketable yield, with both factors showing highly significant results ($P < 0.001$) in 2022, with a similar trend in 2023 (**Table 5**). The interaction also showed a trend towards significance ($P = 0.05$), suggesting a potential combined influence of irrigation methods and mulch types on yield outcomes.

3.3.1. Furrow Irrigation

Marketable yields ranged from 8.91 to 12.92 t ha^{-1} in 2022 and 9.45 to 13.30 t ha^{-1} in 2023, while total yields ranged from 9.91 to 13.92 t ha^{-1}. The addition of maize residue mulch significantly increased yield under furrow irrigation, with a mean boost of approximately 4.01 t ha^{-1} over the control ($p < 0.05$), highlighting maize residue's potential in optimizing yield despite furrow irrigation's lower efficiency.

3.3.2. Drip Irrigation with Chameleon Sensors

This method produced the highest marketable yields, with values from 14.47 to 22.80 t ha^{-1} in 2022 and 15.00 to 23.10 t ha^{-1} in 2023, and total yields from 15.47 to 23.80 t ha^{-1}. Utilizing Chameleon sensors significantly enhanced yield, with up to an 8.33 t ha^{-1} increase over the control ($p < 0.05$). This emphasizes the benefits of sensor technology in maximizing irrigation efficiency and yield outcomes.

3.3.3. Drip Irrigation without Sensors

Marketable yields for this method were between 12.92 to 18.70 t ha^{-1} in 2022 and 13.40 to 18.95 t ha^{-1} in 2023, while total yields ranged from 13.92 to 19.70 t ha^{-1}. Although effective, it delivered yields approximately 3.88 t ha^{-1} lower than sensor-assisted drip irrigation ($p < 0.05$), underscoring the added value of sensors in further improving efficiency.

Table 5. Marketable yield (t ha^{-1}) for different irrigation methods and mulch types (2022 and 2023).

Irrigation Method	Control		Maize Residue		Soya Bean Trash		Grass		Mean Marketable Yield		CV%	SE	LSD
	(2022)	(2023)	(2022)	(2023)	(2022)	(2023)	(2022)	(2023)	(2022)	(2023)			
Furrow irrigation	8.91^{a}	9.45	12.92^{b}	13.30	10.66^{c}	11.12	9.90^{c}	10.20	10.60^{c}	11.02	12%	1.76	3.50
Drip with sensors	14.47^{d}	15.00	22.80^{e}	23.10	20.53^{d}	20.80	16.92^{d}	17.30	18.68^{d}	19.05	16%	2.47	4.95
Drip without sensors	12.92^{c}	13.40	18.70^{d}	18.95	16.86^{c}	17.20	14.70^{c}	15.10	15.80^{c}	16.16	19%	3.15	6.35
Mean marketable yield	12.10	12.62	18.14	18.45	16.02	16.38	13.84	14.20	15.0	12.2	21%	3.52	7.20

Note: Values in parentheses represent the average bulb weight for the 2023 winter season. The mean separation letters (a, b, c, d, e) indicate groups that are statistically similar based on the analysis of variance (ANOVA) conducted on the data from both years (2022 and 2023). For instance, treatments sharing the same letter are not significantly different from each other, highlighting comparable performance in bulb weight across the two seasons. This ensures that any observed differences in average bulb weight can be attributed to the irrigation methods and mulch types rather than seasonal variability.

3.3.4. Impact of Mulching Conditions on Yield

1. Control (No Mulch): Marketable yields for the control were the lowest, ranging from 8.91 to 12.92 t ha^{-1} in 2022 and 9.45 to 13.30 t ha^{-1} in 2023, with total yields spanning 9.91 to 13.92 t ha^{-1}. These yields were significantly lower than all other mulch treatments ($p < 0.05$), confirming mulching's positive role in boosting yield.
2. Grass Mulch: Grass mulch marketable yields ranged from 9.90 to 16.92 t ha^{-1} in 2022 and 10.20 to 17.30 t ha^{-1} in 2023, showing improvement over the control but falling short of maize residue and soybean trash by 1.92 to 5.88 t ha^{-1} ($p < 0.05$). Total yields were between 10.90 to 17.92 t ha^{-1}.
3. Maize Residue: Maize residue application led to the highest marketable yields, ranging from 12.92 to 22.80 t ha^{-1} in 2022 and 13.30 to 23.10 t ha^{-1} in 2023, with a notable 4.01 to 9.88 t ha^{-1} increase over the control ($p < 0.05$). Total yields ranged from 13.92 to 23.80 t ha^{-1}, making maize residue the most effective mulch type.
4. Soya Bean Trash: Marketable yields with soybean trash ranged from 10.66 to 20.53 t ha^{-1} in 2022 and 11.12 to 20.80 t ha^{-1} in 2023, exceeding the control and grass mulch by 1.75 to 8.61 t ha^{-1} ($p < 0.05$). Total yields ranged from 11.66 to 21.53 t ha^{-1}, indicating soybean trash as a viable mulching option, although maize residue outperformed it.

3.4. Water Productivity and Water Use Efficiency Analysis

Gross Irrigation Applied

Table 6 summarizes the gross irrigation applied for each treatment, taking into account the irrigation methods used and the rainfall received during the growing season. The table provides a comparison of gross irrigation applied, total water applied, yield, and water-related efficiency metrics for various irrigation treatments:

1. Drip Irrigation with Sensors: This method achieved the highest yield of 25 t ha^{-1}, resulting in a water productivity (WP) of 0.0093 t m^{-3} and a water use efficiency (WUE) of 0.0093 t m^{-3}.
2. Drip Irrigation without Sensors: This approach yielded 23 t ha^{-1}, maintaining a competitive WP of 0.0072 t m^{-3} and WUE of 0.0072 t m^{-3}.
3. Furrow Irrigation: This method resulted in a lower yield of 20 t ha^{-1}, with a WP of 0.0042 t m^{-3} and WUE of 0.0042 t m^{-3}, indicating less efficiency in water use.
4. Control Treatment (No Mulch): This treatment yielded the least at 18 t ha^{-1}, with a WP of 0.0035 t m^{-3} and WUE of 0.0035 t m^{-3}.

3.5. Interactions between Irrigation and Mulching

The correlation analysis performed in this study highlights significant relationships among the variables yield, marketable yield, and average bulb weight (**Table 7**).

Relationships among Yield, Marketable Yield, and Average Bulb Weight

- Yield and marketable yield: A robust positive cor-

Table 6. Gross irrigation, yield, water productivity (WP), and water use efficiency (WUE) in onion cultivation (2022 and 2023).

Treatment	Gross Irrigation Applied (m^3 ha^{-1})	Rainfall (m^3 ha^{-1})	Total Water Applied (m^3 ha^{-1})	Yield (t ha^{-1})	WP (t m^{-3})	WUE (t m^{-3})
Drip irrigation with sensors	2550	130 (2022)/60 (2023)	2680/2610	25	0.0093	0.0093
Drip irrigation without sensors	3050	130 (2022)/60 (2023)	3180/3110	23	0.0072	0.0072
Furrow irrigation	4600	130 (2022)/60 (2023)	4730/4660	20	0.0042	0.0042
Control (no mulch)	5050	130 (2022)/60 (2023)	5180/5110	18	0.0035	0.0035

relation of 0.95 indicates that increases in total production are closely linked to a rise in the quantity of bulbs that meet market quality standards.

- Yield and average bulb weight: The correlation coefficient of 0.89 implies that higher yields are associated with larger bulb sizes, likely resulting from favourable growing conditions.
- Marketable yield and average bulb weight: A positive correlation of 0.87 indicates that as marketable yield increases, the average weight of the bulbs also tends to increase.

3.6. Economic Implications of Mulching Treatments in Onion Production

The cost-benefit analysis (CBA) was conducted using a partial budget approach to assess the economic viability of four mulching treatments (maize residue, soybean trash, grass, and a control group with no mulch). This analysis examined parameters such as mulch costs, yield data, revenue generation, cost savings, and net benefits, which are summarized in **Table 8** below.

3.6.1. Yield and Revenue Analysis of Mulching Treatments in Onion Production

The evaluation of mulching treatments in onion production reveals significant differences in yield and revenue generation among the various options. As presented in **Table 8**, maize residue emerged as the most productive treatment, achieving a yield increase of 3.85 tons per hectare. This substantial yield translated into a remarkable revenue increase of $1,925 in 2022 and $1,585 in 2023, highlighting the economic advantages of using maize residue as mulch.

Following maize residue, soybean trash demonstrated a yield increase of 2.30 tons per hectare, resulting in a revenue increase of $1,150 in 2022 and $805 in 2023. The grass mulch treatment offered a more modest yield increase of 1.50 tons per hectare, leading to a revenue increase of $780. In stark contrast, the control group, which did not utilize any mulch, resulted in no yield increase or revenue generation, underscoring the critical role of mulching in enhancing onion productivity.

3.6.2. Net Benefit Analysis

The net benefit analysis reveals the economic viability of the mulching treatments. Maize residue achieved a net benefit of $1,615 per hectare in 2022 and $1,585 in 2023, establishing it as the most profitable option among the treatments evaluated. Conversely, soybean trash provided a net benefit of $835 in 2022 and $805 in 2023. Grass mulch, while contributing positively to yield, yielded a stable net benefit of $430 across both years. The control group, however, displayed a negative net benefit of –$300, highlighting the detrimental economic impact of not employing any mulching strategy.

4. Discussion

The findings from the 2022 and 2023 studies on onion cultivation reveal critical insights into the impact of various irrigation methods on Gross Irrigation, Yield, Water Productivity (WP), and Water Use Efficiency (WUE). The comparative analysis of these parameters illustrates the significant advantages of advanced irrigation technologies, particularly sensor-equipped drip irrigation systems.

4.1. Implications of Irrigation Frequency on Crop Productivity

The study demonstrates significant variations in irrigation frequency across different onion cultivation techniques. Drip irrigation with Chameleon sensors, allowing irrigation every 2 to 3 days, is identified as the most effective method for maintaining optimal soil

Table 7. Correlation matrix for yield and marketable yield, and average bulb weight.

Variable	Yield	Marketable Yield	Average Bulb Weight
Yield	1	0.95	0.89
Marketable yield	0.95	1	0.87
Average bulb weight	0.89	0.87	1

moisture. This technology promotes efficient water use and prevents over-irrigation by relying on real-time soil moisture data[7, 8, 11, 15, 18]. In contrast, drip irrigation without sensors, which operates on a fixed schedule of every 4 to 5 days, may lead to suboptimal moisture conditions. Traditional furrow irrigation, requiring watering every 5 to 7 days, is the least efficient, resulting in greater evaporation losses and inconsistent soil moisture that can adversely affect onion growth.

These findings highlight the critical need for advanced irrigation technologies, like sensor-based systems, to enhance water use efficiency (WUE) and improve crop yields. This transition is vital for smallholder farmers facing water scarcity and climate variability challenges. Investing in such innovations not only supports sustainable agricultural practices but also promotes better economic outcomes and resilience within farming communities[3, 10, 11, 15, 18].

Advantages of Drip Irrigation with Chameleon Sensors

Drip irrigation with Chameleon sensors offers significant benefits in terms of water use efficiency (WUE) due to their ability to provide precise, real-time soil moisture data. By measuring soil moisture tension, these sensors allow farmers to apply water only when and where it is needed, minimizing waste and preventing over-irrigation. The study demonstrates that the use of drip irrigation with Chameleon sensors leads to enhanced WUE by allowing for precise irrigation scheduling based on real-time soil moisture data. This targeted approach minimizes water waste and ensures that crops receive adequate moisture, thereby maximizing productivity while conserving water resources[2, 7, 10, 15]. As discussed in Section 4.2.1, the analysis shows that using these technologies significantly improves yield performance compared to traditional methods, with drip irrigation with sensors achieving a yield of 25 t ha^{-1} and a corresponding WUE of 0.0093 t m^{-3}. This reinforces the study's aim to foster the application of these technologies in the cultivation of Texas Grano onions (*Allium cepa*).

4.2. Yield Performance across Irrigation Methods

Water Productivity and Water Use Efficiency Analysis

The analysis of water productivity (WP) and water use efficiency (WUE) further highlights the benefits of precision irrigation techniques. As summarized in **Table 6**, drip irrigation with sensors achieved the highest yield of 25 t ha^{-1}, resulting in a WP of 0.0093 t ma^{-3} and a WUE of 0.0093 t m^{-3}. These metrics illustrate a clear advantage in resource use, demonstrating that sensor-based irrigation not only maximizes yields but also optimizes the efficiency of water use. This aligns with findings from[2, 7, 8, 10, 11] who demonstrated that integrating soil moisture sensors significantly reduces water usage while maintaining or increasing crop yields. The study clearly demonstrates that the implementation of drip irrigation with Chameleon sensors leads to enhanced WUE by allowing for precise irrigation scheduling based on real-time soil moisture data. This targeted approach minimizes water waste and ensures that crops receive adequate moisture, thereby maximizing productivity while conserving water resources[4, 6, 15, 19]. Similarly, Tiruye et al.[20], demonstrated that efficient water management technologies significantly improve water productivity and nutrient balances for irrigated crops.

Conversely, drip irrigation without sensors yielded 23 t ha^{-1}, maintaining a competitive WP of 0.0072 t m^{-3} and WUE of 0.0072 t m^{-3}. Although slightly less efficient than the sensor-equipped system, this method still demonstrates the benefits of drip irrigation over traditional methods. In contrast, furrow irrigation resulted in a lower yield of 20 t ha^{-1}, with a WP and WUE of

Table 8. Cost-benefit analysis of mulching treatments in onion production.

Parameter	Maize Residue	Soybean Trash	Grass	Control (No Mulch)
Cost of mulch	$50	$45	$40	$0
Application cost	$10	$10	$10	$0
Fertilizer cost (2022)	$200	$200	$200	$200
Fertilizer cost (2023)	$230	$230	$230	$230
Labor cost	$100	$100	$100	$100
Total cost (2022)	$360	$355	$350	$300
Total cost (2023)	$390	$385	$380	$300
Market price of onions (per ton)	$500	$500	$500	$500
Cost savings	$50	$40	$30	$0
Total benefits	$1,975	$1,190	$780	$0
Yield increase (tons)	3.85	2.30	1.50	0.00
Market price of onions (per ton)	$500	$500	$500	$500
Revenue increase (2022)	$1,925	$1,150	$750	$0
Revenue increase (2023)	$1,585	$805	$750	$0
Cost savings	$50	$40	$30	$0
Total benefits	$1,975	$1,190	$780	$0
Net benefit (2022)	$1,615	$835	$430	–$300
Net benefit (2023)	$1,585	$805	$430	–$300

Notes:

1. Cost of Mulch: This includes the expenses associated with the materials used for mulching treatments (maize residue, soybean trash, and grass), which contribute to moisture retention and weed suppression in onion production.
2. Application Cost: This refers to the consistent expenses incurred for applying the mulch materials across all treatments.
3. Fertilizer Cost: Fertilizer costs are indicated for both years to demonstrate changes in input expenses. The increase from 2022 to 2023 reflects market fluctuations and inflation, impacting overall production costs.
4. Labor Cost: The labor cost of $100 per hectare remains constant for both years, reflecting standard expenses for the application and management of the mulching treatments.
5. Total Cost: Total costs represent the sum of all input costs (mulch, application, fertilizer, and labor) for each treatment in both years. The control treatment (no mulch) shows significantly lower total costs but results in no yield increase.
6. Yield Increase: The yield increase is expressed in tons per hectare and reflects the additional onion production achieved through the application of different mulching treatments compared to the control.
7. Market Price of Onions: The market price of onions is assumed to be constant at $500 per ton for this analysis, although actual prices may vary based on market conditions.
8. Net Benefit: Net benefits are calculated as the difference between revenue increases and total costs. Negative net benefits indicate losses associated with the control treatment, underscoring the economic advantages of mulching.
9. The term "per hectare" has been removed from the table headings to streamline presentation, as all values are inherently based on a per-hectare assessment. Key findings indicate that maize residue provides the most significant yield increase of 3.85 tons and a net benefit of $1,585 after accounting for increased fertilizer costs, highlighting its economic viability in onion production.

$0.0042\ \mathrm{t\,m^{-3}}$, indicating less efficiency in water use. The control treatment (no mulch) yielded the least at 18 $\mathrm{t\ ha^{-1}}$, with a WP and WUE of $0.0035\ \mathrm{t\ m^{-3}}$, reinforcing the notion that insufficient irrigation strategies lead to decreased productivity. The results highlight the critical role of irrigation technology in enhancing water productivity (WP) and water use efficiency (WUE). For instance, [1–5, 7, 8, 10, 11, 15, 19, 20] found that precision irrigation systems, including those using Chameleon sensors, optimize water use efficiency through accurate soil moisture data, which helps in making informed irrigation decisions. Furthermore, Lakhiar et al. and Abebe et al. [17, 18], demonstrated that smallholder farms employing advanced irrigation systems show improved water efficiency and crop performance, supporting the notion that such technologies are essential for sustainable agricultural practices.

4.3. Economic Benefits and Sustainability Implications of Mulching Practices

The economic analysis of various mulching treatments highlights the substantial benefits of integrating precision irrigation and mulching practices in onion production. The cost-benefit analysis demonstrated that maize residue mulch achieved the highest net benefit of $1,615 per hectare in 2022 and $1,585 per hectare in 2023 (**Table 8**), representing the most favorable return on investment among the mulching options. This finding reinforces the notion that sustainable agricultural practices can lead to significant economic advantages for farmers, aligning with previous studies that emphasize the economic benefits of organic mulches for improving crop performance [9, 11, 18, 21].

The notable increase in yield, with maize residue providing a yield increase of 3.85 tons per hectare, coupled with significant cost savings of $50 per hectare for irrigation and weed management, positions maize residue as a highly efficient choice for enhancing onion production while minimizing overall input expenses. This economic implication extends beyond immediate cost savings; it contributes to the long-term sustainability of farming operations by promoting soil health and resilience [12, 22].

In contrast, while soybean trash offered considerable economic advantages with a net benefit of $835 per hectare in 2022 and $805 per hectare in 2023, it did not match the net benefit of maize residue. Nonetheless, it still provided a substantial yield increase of 2.30 tons per hectare and cost savings of $40 per hectare, making it a practical option for farmers aiming to boost their productivity and profitability. Grass mulch, resulting in a net benefit of $430 per hectare in both years, demonstrated lower yield increases compared to maize residue and soybean trash but still provided some economic advantages, particularly in maintaining soil moisture and temperature [14, 23].

4.4. Implications, Considerations, and Directions for Smallholder Farmers

4.4.1. Implications for Smallholder Farmers

The findings from this study highlight the significant economic advantages associated with the application of mulch, particularly maize residue. This type of mulch has emerged as the most beneficial option for smallholder farmers, offering a cost-effective method to enhance crop yields while simultaneously minimizing overall input expenses. By utilizing maize residue, farmers can improve their onion production and reduce reliance on costly inputs such as fertilizers and pesticides, thereby increasing their profit margins.

Additionally, the use of mulch serves a dual purpose: it boosts crop yields and leads to substantial cost reductions. By decreasing the need for additional irrigation and reducing the frequency of weed control measures, mulching becomes an essential agricultural practice for smallholder farmers. This cost efficiency is particularly critical for farmers operating with limited resources, as it allows them to allocate their finances more effectively while achieving high levels of productivity.

The economic implications of adopting these practices extend beyond immediate cost savings; they contribute to the long-term sustainability of farming operations by promoting soil health and resilience. For smallholder farmers, the adoption of these practices can lead to improved food security and economic stability in their communities. Enhanced onion production can contribute to local markets, providing fresh produce and increasing farmers' incomes [22–25].

4.4.2. Environmental Considerations

The environmental benefits of adopting precision irrigation and mulching practices are significant. By enhancing water-use efficiency, these practices help conserve water resources, which is becoming increasingly crucial due to climate change and rising water scarcity. Additionally, employing organic mulches, such as maize residue, improves soil health by boosting organic matter levels, enhancing soil structure, and fostering beneficial microbial activity.

These environmental benefits extend beyond individual farms, contributing to broader ecosystem health. Healthy soils are more resilient to erosion and degradation, supporting biodiversity and ecosystem services that are vital for sustainable agriculture. Furthermore, by decreasing reliance on chemical fertilizers and pesticides, mulching practices can result in reduced agricultural runoff, thereby safeguarding the water quality of nearby streams and rivers [6, 8, 9, 11, 12, 14, 18, 19, 23, 25].

4.4.3. Socio-Economic Factors

The socio-economic factors influencing the adoption of precision irrigation and mulching practices among smallholder farmers warrant further investigation. Key barriers include access to credit, knowledge gaps, and resource limitations [11]. Understanding these barriers can inform targeted interventions that promote sustainable agricultural practices.

- Access to Financial Resources: Many smallholder farmers struggle with limited access to credit due to perceived risks by financial institutions. Targeted microfinance programs or subsidies could alleviate these financial barriers and encourage broader adoption of precision irrigation and mulching practices [10].
- Education and Knowledge Transfer: Low educational levels can hinder farmers' understanding of modern techniques. Enhancing extension services and farmer training programs can provide crucial knowledge about technology benefits and implementation strategies [4, 10, 12, 19].
- Social Networks: Membership in farmer organizations can facilitate resource sharing and collective action, enhancing market participation [11, 19].
- Gender Dynamics: Addressing gender disparities is vital for ensuring that both male and female farmers benefit from sustainable practices [10].
- Infrastructure Challenges: Improving infrastructure is necessary to support market access for smallholders [24].

4.4.4. Policy Recommendations

To effectively address socio-economic barriers, policymakers should consider the following strategies:

Developing Targeted Microfinance Programs: These programs should provide accessible credit options specifically for investments in precision irrigation and mulching.

Enhancing Agricultural Extension Services: Focus on education and training related to sustainable practices to empower farmers with the knowledge they need.

Establishing Innovation Hubs: Creating hubs within irrigation schemes can promote farmer organization membership, facilitating resource sharing, knowledge exchange, and technology adoption among farmers, thereby enhancing productivity and market access for high-value crops [5, 7, 10, 11, 15, 19].

To implement these policy recommendations effectively, specificity in execution is essential. Policymakers could introduce a subsidy scheme that covers a percentage of the costs associated with purchasing precision irrigation equipment. Additionally, establishing Farmer Field Schools (FFS) can facilitate hands-on training in precision irrigation and mulching practices. These training programs should include workshops and demonstration trials conducted in Lead Farmer fields to showcase successful case studies and the tangible benefits of adopting these technologies [11, 19].

4.5. Study Limitations

Controlled Conditions vs. Field Variability: The study was conducted under controlled conditions, which may not fully reflect the variability encountered in actual field settings.

1. Short Duration of Study: Data collection over two years may not capture the long-term sustainability and impacts of the implemented practices.
2. Limited Geographic Scope: The findings are based on a specific geographic location, potentially limiting their applicability to other regions with different climatic and soil conditions.
3. Technology Adoption Barriers: The study does not extensively explore farmer perceptions or resistance to adopting new precision irrigation and mulching practices.

4.6. Research Gaps and Future Directions

Although this study offers important insights into the advantages of precision irrigation and mulching, several research gaps remain:

1. Long-Term Effects: Future investigations should examine the long-term effects of precision irrigation and mulching on soil health, crop yield, and economic sustainability to assess their viability over extended periods [2].
2. Diverse Organic Mulches: Research should explore the effects of different types of organic mulches on various crops, as the impact of mulch can vary significantly depending on the material used [12, 14].

3. Integration of Cover Crops: There is a need to investigate the potential for integrating cover crops into precision irrigation and mulching systems, which could enhance soil health and improve overall crop productivity [9].
4. Farmer Adoption Factors: Further studies should focus on understanding the socio-economic factors influencing farmer adoption of these practices, including access to resources and training, to facilitate broader implementation in diverse agricultural contexts [11, 18].

5. Conclusions

This study highlights the significant benefits of precision irrigation and mulching in enhancing onion productivity in semi-arid regions. Key findings demonstrate that drip irrigation equipped with Chameleon sensors markedly improves water use efficiency, allowing for real-time moisture management and resulting in higher yields compared to traditional methods. Additionally, the use of maize residue mulching enhances moisture retention, soil health, and nutrient availability, contributing to greater resilience against climate stressors.

Smallholder farmers can achieve economic gains by adopting these practices, as they lead to reduced input costs and increased profitability. The research underscores the need for supportive policies and resources to encourage the adoption of these innovative technologies.

Ultimately, the combination of advanced irrigation and effective mulching not only fosters sustainable agricultural practices but also enhances food security and promotes environmental stewardship, paving the way for a more resilient agricultural landscape.

Author Contributions

Conceptualization, J.N., L.-L.S., and V.S.; methodology, J.N., L.-L.S., L.M. (Linda Munyaradzi), and A.M.; software, G.M.; validation, J.N., A.M., and G.M.; formal analysis, G.M.; investigation, J.N., A.M., L.M. (Leonard Madzingaidzo), and L.-L.S.; resources, V.S.; data curation, G.M., A.M., and J.K.N.; writing—original draft preparation, J.N.; writing—review and editing, J.N., G.M., A.M., and L.-L.S.; visualization, G.M.; supervision, project administration and funding acquisition, L.M. (Linda Munyaradzi). All authors have read and agreed to the published version of the manuscript. Authorship is limited to those who have contributed substantially to the work reported.

Funding

This research was supported by the Korea Africa Food and Agriculture Cooperation Initiative.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the results presented in this article are available and can be accessed by the public at no cost. For further details or specific inquiries, please contact the corresponding author at jknzumayahoo.com.

Acknowledgments

We extend our sincere gratitude to our extension partners, Agricultural Rural Development and Advisory Services (ARDAS) in Zimbabwe, for their invaluable support and assistance throughout this study. Their knowledge and commitment have been crucial to the success of our research.

We also wish to acknowledge the significant support provided by the stage gate teams at the Scientific and Industrial Research and Development Centre (SIRDC) and Chiredzi Research Institute. Their collaboration and resources have greatly facilitated our research efforts.

Conflicts of Interest

The authors declare that they have no financial or personal relationships that might be viewed as potential conflicts of interest in the execution and reporting of this research.

References

[1] Moursy, M.A.M., ElFetyany, M., Meleha, A.M.I., et al., 2023. Productivity and profitability of modern irrigation methods through the application of on-farm drip irrigation on some crops in the Northern Nile Delta of Egypt. Alexandria Engineering Journal. 62, 349–356. DOI: https://doi.org/10.1016/j.aej.2022.06.063

[2] Yu, L.M., Gao, W.L., Shamshiri, R.R., et al., 2021. Review of research progress on soil moisture sensor technology. International Journal of Agricultural and Biological Engineering. 14(4), 32–42. DOI: https://doi.org/10.25165/j.ijabe.20211404.6404

[3] Yang, P., Wu, L., Cheng, M., et al., 2023. Review on Drip Irrigation: Impact on Crop Yield, Quality, and Water Productivity in China. Water, 15(9), 1733. DOI: https://doi.org/10.3390/w15091733

[4] Bwambale, E., Abagale, F.K. Anornu, G.K., 2022. Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. Agricultural Water Management. 260, 107324. DOI: https://doi.org/10.1016/j.agwat.2021.107324

[5] Levidow, L., Zaccaria, D., Maia, R., et al., 2014. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. Agricultural Water Management. 146, 84–94. DOI: https://doi.org/10.1016/j.agwat.2014.07.012

[6] Zhang, X., Feng, G., Sun, X., 2024. Advanced technologies of soil moisture monitoring in precision agriculture: A Review. Journal of Agriculture and Food Research. 18, 101473. DOI: https://doi.org/10.1016/j.jafr.2024.101473

[7] Stirzaker, R., Driver, M., 2024. Soil water sensors that display colours as thresholds for action. International Journal of Water Resources Development. 1–19. DOI: https://doi.org/10.1080/07900627.2024.2322153

[8] Mdemu, M., Kissoly, L., Bjornlund, H., et al., 2020. The role of soil water monitoring tools and agricultural innovation platforms in improving food security and income of farmers in smallholder irrigation schemes in Tanzania. International Journal of Water Resources Development. 36(Suppl. 1), S148–S170. DOI: https://doi.org/10.1080/07900627.2020.1765746

[9] Vanella, D., Guarrera, S., Ferlito, F., et al., 2025. Effects of organic mulching and regulated deficit irrigation on crop water status, soil and yield features in an orange orchard under Mediterranean climate. Science of The Total Environment. 958, 177528. DOI: https://doi.org/10.1016/j.scitotenv.2024.177528

[10] Moyo, M., Van Rooyen, A., Bjornlund, H., et al., 2020. The dynamics between irrigation frequency and soil nutrient management: transitioning smallholder irrigation towards more profitable and sustainable systems in Zimbabwe. International Journal of Water Resources Development. 36(1), 102–126. DOI: https://doi.org/10.1080/07900627.2020.1739513

[11] Chilundo, M., De Sousa, W., Christen, E.W., et al., 2020. Do agricultural innovation platforms and soil moisture and nutrient monitoring tools improve the production and livelihood of smallholder irrigators in Mozambique? International Journal of Water Resources Development. 36(1), 127–147. DOI: https://doi.org/10.1080/07900627.2020.1760799

[12] Mupangwa, W., Nyagumbo, I., Mutsamba, E., 2016. Effect of various mulching materials on maize growth and yield in conservation agriculture systems of sub-humid Zimbabwe. AIMS Agriculture and Food. 1(2), 239–253. DOI: https://doi.org/10.3934/agrfood.2016.2.239

[13] Bjornlund, H., Van Rooyen, A., Stirzaker, R., 2017. Profitability and productivity barriers and opportunities in small-scale irrigation schemes. International Journal of Water Resources Development. 33(5), 690–704. DOI: https://doi.org/10.1080/07900627.2016.1263552

[14] Nouri, H., Stokvis, B., Galindo, A., et al., 2019. Water scarcity alleviation through water footprint reduction in agriculture: The effect of soil mulching and drip irrigation. Science of The Total Environment. 653, 241–252. DOI: https://doi.org/10.1016/j.scitotenv.2018.10.311

[15] Stirzaker, R., Mbakwe, I., Mziray, N.R., 2017. A soil water and solute learning system for small-scale irrigators in Africa. International Journal of Water Resources Development. 33(5), 788–803. DOI: https://doi.org/10.1080/07900627.2017.1320981

[16] Climate-Data.org, 2022–2023. Climate: Chiredzi. Climate-Data.org. Available from: https://en.climate-data.org/africa/zimbabwe/masvingo-province/chiredzi-55090/

[17] Lakhiar, I.A., Yan, H., Zhang, C., et al., 2024. A Review of Precision Irrigation Water-Saving Technology under Changing Climate for Enhancing Water Use Efficiency, Crop Yield, and Environmental Footprints. Agriculture. 14, 1141. DOI: https://doi.org/10.3390/agriculture14071141

[18] Abebe, F., Zuo, A., Wheeler, S.A., et al., 2020. Irrigators' Willingness to Pay for the Adoption of Soil Moisture Monitoring Tools in South-Eastern

Africa. International Journal of Water Resources Development. 36(Suppl. 1), S246–S267. DOI: https://doi.org/10.1080/07900627.2020.1755956

[19] Van Rooyen, A.F., Ramshaw, P., Moyo, M., et al., 2017. Theory and application of Agricultural Innovation Platforms for improved irrigation scheme management in Southern Africa. International Journal of Water Resources Development. 33(5), 804–823. DOI: https://doi.org/10.1080/07900627.2017.1321530

[20] Tiruye, A.E., Asres Belay, S., Schmitter, P., et al., 2022. Yield, water productivity and nutrient balances under different water management technologies of irrigated wheat in Ethiopia. PLoS Water. 1(12), e0000060. DOI: https://doi.org/10.1371/journal.pwat.0000060

[21] Kumar, P., Lata, S., Swapnil, S.A., et al., 2022. Effect of Tillage and Mulching on Growth, Yield and Economics of Maize Crops. International Journal of Bioresource and Stress Management. 13(4), 332–338. DOI: https://doi.org/10.23910/1.2022.2362a

[22] Qin, W., Hu, C., Oenema, O., 2015. Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis. Scientific Reports. 5, 16210. DOI: https://doi.org/10.1038/srep16210

[23] Ayala, G., Bulti, A., Muleta, B., 2023. Evaluation of Mulching and Tied Ridges on Soil Moisture and Yield of Maize at Daro Lebu District, Western Hararghe Zone, Oromia, Ethiopia. International Journal of Agricultural Economics. 8(3), 116–121. DOI: https://doi.org/10.11648/j.ijae.20230803.16

[24] Adetoro, A.A., Abraham, S., Paraskevopoulos, A.L., et al., 2020. Alleviating water shortages by decreasing water footprint in sugarcane production: The impacts of different soil mulching and irrigation systems in South Africa. Groundwater for Sustainable Development. 11, 100464. DOI: https://doi.org/10.1016/j.gsd.2020.100464

[25] Telila, R.G., Naneso, D.A., Diriba, M.E., et al., 2024. Evaluation of different moisture conservation practices on maize production and productivity in Dallomanna Districts of Bale Lowland Southeastern Ethiopia. Journal of Scientific Agriculture. 8, 59–65. DOI: https://doi.org/10.25081/jsa.2024.v8.8995