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Water-nitrogen Management under Supplementary Irrigation through Rainwater Harvesting Technique for Improving Soil Fertility, Tomato Yield and Water Productivity in the West African Sahel

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Authors' contributions

This work was carried out in collaboration among all authors. Author ASK did the conceptualization, methodology, data curation, formal analysis, software, validation, writing – original draft, review & editing. Author BWBS did the data collection, writing – review & editing. Author MW did the writing – review & editing. Author EK did the writing – review & editing. Author BB did the writing – review & editing. Author YMW did the validation, visualization, writing – review & editing. All authors read and approved the final manuscript.

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Original Research Article

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Abstract

Supplementary irrigation using harvested water is widely promoted in Burkina Faso and is increasingly adopted nationally as a suitable practice for sustaining and/or improving rain-fed production. However, under current land degradation conditions, this approach should be sustainable, with optimal water amounts matched to N fertiliser to optimise productivity while improving soil fertility. A two-year (2023 and 2024) split-plot field experiment was conducted at Gomtoaga village (12.24° N and 1.24° W), Koubri District, Burkina Faso, to identify an optimal water-nitrogen combination for improving soil fertility, yield, and water-use efficiency. Two forms of urea, pearled urea (PU) and deep placement of super granule urea (DPU), were combined with three water amounts (D100, D75, and D50), representing 100%, 75%, and 50% of tomato net irrigation, respectively. The results indicated that the PU + D75 combination increased soil microbial CO_2 release (152%), microbial biomass (145%), OM (210%), C (215%), N (44%), and yield (34%), whereas DPU + D75 increased soil P (121%) and K (324%). The highest water productivity (43.34 kg/m^3) and the lowest water cost (55.52 F CFA) for producing 1 kg of tomato were obtained under DPU + D50. Therefore, DPU + D50 and PU + D75 may be considered adapted practices for coping with water scarcity and improving land productivity, respectively. A cost-benefit analysis is required to identify the most beneficial combination by balancing farm returns and sustainable production.

Keywords: Rainwater harvesting; supplementary irrigation management; water productivity; urea forms; nitrogen management; soil fertility; tomato yield.

1. Introduction

Concern is increasing globally about securing production, especially in countries such as Burkina Faso, where agriculture is largely rainfall-based. The country's agriculture is rain-dependent, and crops experience rainwater deficit stress every year (Kima *et al.*, 2020). Erratic rainfall and intermittent droughts lead to declining yields and slower production growth (Africa Rice Center, 2007; Rockström *et al.*, 2009). Drought is the primary environmental constraint adversely affecting farmers in Burkina Faso (Traoré *et al.*, 2020), and yield reductions result from insufficient rainfall (Traore *et al.*, 2016a, 2016b). Water-deficit stress is one of the major environmental disturbances causing severe yield reductions in many crops (Bekele *et al.*, 2019).

The current increase in water scarcity requires investment in, and adoption of, sustainable strategies to secure rain-fed production, particularly in developing countries (Ogbiye *et al.*, 2021). A vital strategy is to mitigate the risk of dry spells, which calls for emphasis on supplemental irrigation through rainwater harvesting (Rockström *et al.*, 2010; Fossi *et al.*, 2013; Adams, 2017). Harvesting rainwater for supplementary irrigation helps address water shortage and drought in arid and semi-arid areas (Kaboré *et al.*, 2024) by increasing yield by up to about 25% (Barbier *et al.*, 2015). Harvesting and reusing rainwater through supplemental irrigation provides a usable water source that helps overcome drought spells. In supplementary irrigation, additional water is supplied to bridge the gap between rainfall events and mitigate drought. Supplying additional water when rainfall fails to meet crop water requirements can improve and/or stabilise yield (Tuo *et al.*, 2023; Lei *et al.*, 2022). Rainwater harvesting is crucial for stabilising production in rain-fed agricultural systems (Domullodzhanov, 2023; Raimondi *et al.*, 2023), and irrigation plays a critical role in increasing yield (Begna, 2020; Tessema & Simane, 2021; Kima *et al.*, 2025a).

Recent reviews on deficit irrigation and precision water management also emphasise that water-saving strategies should be applied according to crop stage and local water availability to avoid unnecessary yield penalties (Jadhav *et al.*, 2026).

In recent years, rainwater harvesting for supplementary irrigation has gained increased attention as a sustainable solution for securing rain-fed production in Burkina Faso. The use of stormwater retention basins and supplementary irrigation has been promoted by the Government of Burkina Faso (Ouedraogo *et al.*, 2024; Kima *et al.*, 2025b). The technique has been tested (Zongo *et al.*, 2015; Sanfo *et al.*, 2017; Araya *et al.*, 2024), with attention placed on important vegetable crops such as tomato (Nangare *et al.*, 2016; Mehla & Singh, 2019). When implementing rainwater harvesting techniques, producers prioritise high-value vegetable crops such as tomato (Sanogo *et al.*, 2024). Farmers have adopted the technique, and emergency irrigation is used with limited attention to the amount of water applied. Supplemental water is applied mainly to overcome dry spells, with limited consideration of efficient irrigation water use. Applying additional water without sufficient attention to sustainable depth may lead to water losses through deep percolation and seepage (Kambou *et al.*, 2014). Declining rainfall patterns, coupled with drought frequency, call for sustainable irrigation water management to improve water-use efficiency and productivity. Since rainfall often fails to fill reservoirs sufficiently, optimising water use is a better approach for securing rain-fed production (Kima *et al.*, 2020). Improving water productivity is vital, particularly in drought-prone areas (Wallace, 2000).

Recent regulated deficit-irrigation research in processing tomato indicates that reduced irrigation amounts can conserve water, although crop responses remain dependent on irrigation regime and production context (Xu *et al.*, 2024).

In securing rain-fed agriculture, supplemental water should not be applied to create well-watered conditions but should instead optimise both water-use efficiency and yield (Kima *et al.*, 2015; Bekele *et al.*, 2019). Moreover, water management should not be addressed without considering nutrient uptake by plants, particularly N fertiliser. Since the success and credibility of rainwater collection techniques depend on farm productivity, which is based on the water-fertiliser complex, optimal yield cannot be achieved unless water application is synchronised with plant nitrogen uptake. The application of an inadequate amount of supplemental water may lead to deep percolation, inducing nutrient leaching and, in turn, decreasing yield. Applying additional water at the time of maximum nitrogen uptake should optimise yield and farm profitability. Integrated water-nutrient management is crucial for the success of rainwater harvesting techniques (Fox & Rockström, 2003). Adjusting water application to match optimum water and nutrient uptake by roots should increase yield to an optimal level.

Recent tomato-based work further supports the need to evaluate water and nitrogen together, because their interaction can influence tomato yield and resource-use efficiency (Zhao *et al.*, 2025).

In addition, N-fertiliser uptake by plants depends on nitrogen release, which is influenced by fertiliser form. Previous investigations (Yameogo, 2009; Yao *et al.*, 2018; Faye *et al.*, 2020; Yameogo, 2021) have supported the adoption of deep placement of super granule urea (DPU) as a better practice than pearled urea. These studies indicated that the slow release of nitrogen from granule urea placed at a depth of 7-10 cm improved nitrogen-use efficiency, whereas pearled urea is characterised by quick solubility and high volatilisation losses. Matching nitrogen release according to urea form with a suitable supplemental water amount should improve both water- and nitrogen-use efficiency and, in turn, optimise production.

Recent smallholder-focused soil-water-plant modelling literature similarly indicates that soil moisture regulates nutrient mobility, microbial nitrogen transformations and root uptake, reinforcing the need to synchronise irrigation depth with fertiliser behaviour (Youngoke *et al.*, 2026).

Despite these advances, field evidence remains limited on how harvested supplemental water amounts should be matched with urea form to optimise tomato yield, water productivity and selected soil fertility indicators under the West African Sahel context.

Therefore, identifying an adapted combination may increase farm profitability while securing rain-fed production. However, this approach is rarely employed in vegetable production and remains insufficiently documented. The present study aimed to evaluate supplemental water amounts using different forms of urea through a rainwater harvesting basin to determine a sustainable combination that optimises yield, water productivity, and land productivity.

2. Materials and Methods

2.1 Location Description and Design of Experiment

The experiment was implemented at Gomtoaga village (12.24° N and 1.24° W) in Koubri District, located in the semi-arid climate of central Burkina Faso (Fig. 1). The climate is characterised by a short rainy season from

June to September and a long dry season from October to May. The 25-year (2000-2024) averages of rainfall and temperature varied from 600 mm to 800 mm and from 17 °C to 42 °C, respectively. The soil was sandy-silty-clay, with volumetric humidity of 15.0% at wilting point and 27.5% at field capacity. The trial was carried out over two successive years, 2023 and 2024, from June to August, using a split-plot experimental design with three replications on a total area of 184 m^2. The main treatment consisted of two forms of urea: pearled urea (PU) and deep placement of super granule urea (DPU). The sub-treatment consisted of irrigation depths (D100, D75, and D50), representing 100%, 75%, and 50% of tomato crop net irrigation depth, respectively. Each plot measured 3 m x 2 m, with a distance of 1 m between plots and blocks.

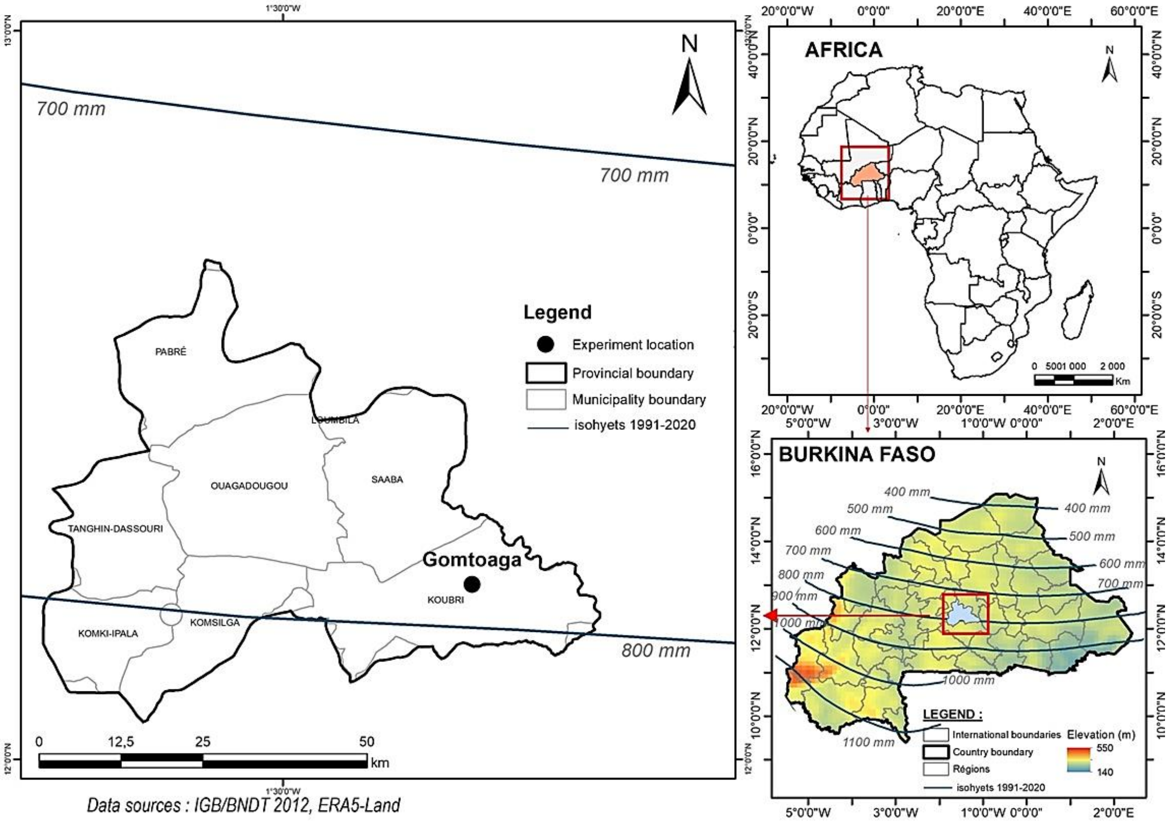

Fig. 1. Location of the experimental site at Gomtoaga village, Koubri district, central Burkina Faso

The main panel shows the administrative boundaries of the Kadiogo province and surrounding municipalities, with the 700 mm and 800 mm mean annual isohyets (1991–2020) indicating the semi-arid climatic context of the study area.

2.2 Field Preparation, Planting and Crop Management

Dry land preparation started on 15 June 2023 and 20 June 2024 by implementing a furrow irrigation system through manual tillage. Furrows were installed at 0.6 m spacing from each other and measured 3 m in length, 0.2 m in width, and 0.15 m in depth. Organic matter was then applied in each furrow at a rate of 10 t/ha and soaked with a ponded water depth of 5 cm. Two weeks after the application of organic matter, 25-day-old seedlings of the Cobra 26 F1 variety were transplanted in each furrow at a spacing of 0.4 m and at a density of 41,600 plants/ha. Transplanting was carried out on 28 June and 5 July in 2023 and 2024, respectively. Cobra 26 F1 is an early-maturing tomato variety (65 days) widely adopted by farmers. After transplanting, water was applied daily to soil saturation when required for 14 days, until the plants overcame transplanting shock.

Fifteen days after transplanting, NPK (14:23:14) fertiliser was hand-broadcast in each furrow at a rate of 250 kg/ha, and irrigation water treatments (D100, D75, and D50) were applied. At the beginning of the flowering stage, pearled urea (PU) and deep placement of super granule urea (DPU) were applied at 180 kg/ha. PU was broadcast, while DPU was placed at a depth of about 7-10 cm, with one 3 g granule between two plants. Pesticides were applied when needed, based on specific pest presence, and hand-weeding was performed frequently.

2.3 Irrigation Scheduling and Application

For irrigation scheduling, 25-year (2000-2024) weather data were extracted from the FAO WaPOR database. The data were used in CROPWAT 8.0 software, and tomato maximum evapotranspiration (ET_{max}) was calculated using the standard FAO Penman-Monteith formula according to planting dates of 28 June and 5 July in 2023 and 2024, respectively. Irrigation parameters such as net irrigation (I_{net}) and irrigation interval (I_i) were calculated. Net irrigation was derived from Equation 1.

$$I_{net} = y\left(H_{fc} - H_{wp}\right)Z_r \tag{1}$$

where I_{net} is net irrigation (mm); y is the tomato crop critical depletion (60%); H_{fc} and H_{wp} represent soil volumetric humidity (%) at field capacity and wilting point, respectively; and Z_r is the root-zone depth (mm).

Since the measured water was directly applied in furrows without significant losses, irrigation efficiency was assumed to be 1; therefore, gross irrigation (I_g) was equal to net irrigation.

The irrigation interval was obtained using Equation 2.

$$I_i = \frac{I_{net}}{ET_{max}} \tag{2}$$

where I_i is the irrigation interval (day), I_{net} is net irrigation (mm), and ET_{max} is maximum evapotranspiration (mm/day).

Irrigation water treatments were applied at the calculated irrigation interval of two days. Irrigation water was supplied to take full advantage of rainwater, as described by Kima *et al.* (2015). When rainfall occurred between two irrigation events or on the irrigation day, water application was postponed to the next irrigation (Kima *et al.*, 2024). Water treatments ended one week before the end of harvest. Table 1 presents the irrigation period alongside the tomato crop growing cycle. In 2023, water treatments were applied four times in July (twice in decade 2) and August (once in both decades 2 and 3), while in 2024, irrigation amounts were supplied six times in July (decades 2 and 3), August (decades 1, 2, and 3), and September (decade 2).

Table 1. Irrigation schedule during growing period

Years	2023	2024
Irrigation dates	July 12th July 15th August 11th August 22nd	July 19th July 27th August 15th August 22nd August 30th September 12th
Total	**4**	**6**

2.4 Soil Sample Collection and Properties Measurement

Soil was sampled at a depth of 0.2 m before and after the two-year experiment for chemical and microbial property analysis. Before the experiment, samples were collected using the median and diagonal method; in total, five samples were taken to establish the initial soil status, which was considered the control. For post-experiment soil analysis after two years, five samples were extracted from the five furrows in each treatment. Five soil samples were then obtained per treatment.

Soil chemical properties such as organic matter (OM), carbon (C), nitrogen (N), potassium (K), and phosphorus (P) were analysed, and the C/N ratio was calculated. The Walkley and Black method (1934) was used to determine soil OM and C. The Kjeldahl method (1883), performed using a spectrophotometer, was used to quantify N and P.

For biological properties, microbial respiration and microbial biomass were analysed. The chloroform fumigation-extraction method developed by Jenkinson and Powlson (1976) was used to measure microbial biomass and activity. Moist soil was first exposed to ethanol-free chloroform ($CHCl_3$) for 24 hours to kill microorganisms. The fumigant was removed, and a 10-day incubation was conducted to measure the resulting flush of CO_2.

2.5 Agronomic Parameters Assessment

After planting, three plants per row were randomly selected for growth and yield measurements. In total, 45 plants were considered per treatment, and measurements were taken from each sampled plant individually. Stem diameter was measured at 55 days after transplanting using a caliper. At ripening, all harvested tomato fruits from each selected plant were weighed to determine fruit weight per plant. Five harvests were completed, and five yield values were recorded. Tomato yield for each harvest and total yield were obtained using Equations 3 and 4, respectively:

$$Y_n = FW_n \times \frac{41600}{1000} \quad (3)$$

$$Y = Y_1 + \cdots + Y_5 \quad (4)$$

where n denotes the number of harvests (varying from 1 to 5); Yn represents yield (kg/ha) at harvest n; FWn is fruit weight (g) per plant at harvest n; 41,600 represents the number of plants per ha; 1000 is the correction factor; and Y is total yield.

2.6 Assessment of Water Productivity and Cost

Water productivity, defined as the yield-to-water ratio, was determined based on the equation described by Geerts and Raes (2009). The cost of water for producing 1 kg of tomato was calculated using the formula described by Kima *et al.* (2025b).

2.7 Statistical Analysis

Statistical analysis was conducted using SPSS 18 software (IBM, Armonk, New York, NY, USA). Analysis of variance (ANOVA) was performed on the data. The statistical significance of treatment effects was established, and means were separated using Duncan's test at 95% confidence. The interaction between years and treatments was analysed through regression to assess the year-dependence effect on the parameters. Years were treated as a fixed factor.

3. Results

3.1 Environmental Conditions during the Production Cycle

Fig. 2 displays effective precipitation and tomato crop water needs (ETR) at the experiment site during the development and flowering stages. In 2023 (Fig. 2A), 50.29 mm of rain was recorded over 5 days during the development stage, with a 10-day dry spell; at the flowering stage, a dry spell of 6 days was observed, and 82.17 mm of rain was recorded over 9 days. In 2024 (Fig. 2B), cumulative rainfall of 51.62 mm was measured over 2 days, and a 13-day drought was observed at the development stage; during flowering, a 9-day rainless period was noted, and 118.73 mm of aggregated rainfall was observed over 6 days. Dry spells were 30% and 50% longer at the development and flowering stages, respectively, in 2024 than in 2023.

Fig. 3 shows daily rainfall and tomato crop daily water requirement at fruit setting and harvest during the two-year experiment. In 2023 (Fig. 3A), total rainfall of 119.91 mm was recorded over 6 days, and a 9-day dry spell was observed at fruit setting; at harvest, 5 days of dry period and accumulated rainfall of 139.75 mm over 15 days were recorded. In 2024 (Fig. 3B), rainfall of 75.75 mm over 4 days and an 11-day drought period were recorded at fruit setting; during harvest, a 13-day drought period and 162.63 mm of rainfall were recorded over 7 days. The drought period was 22% and 73% longer at fruit setting and harvest, respectively, in 2024 than in 2023.

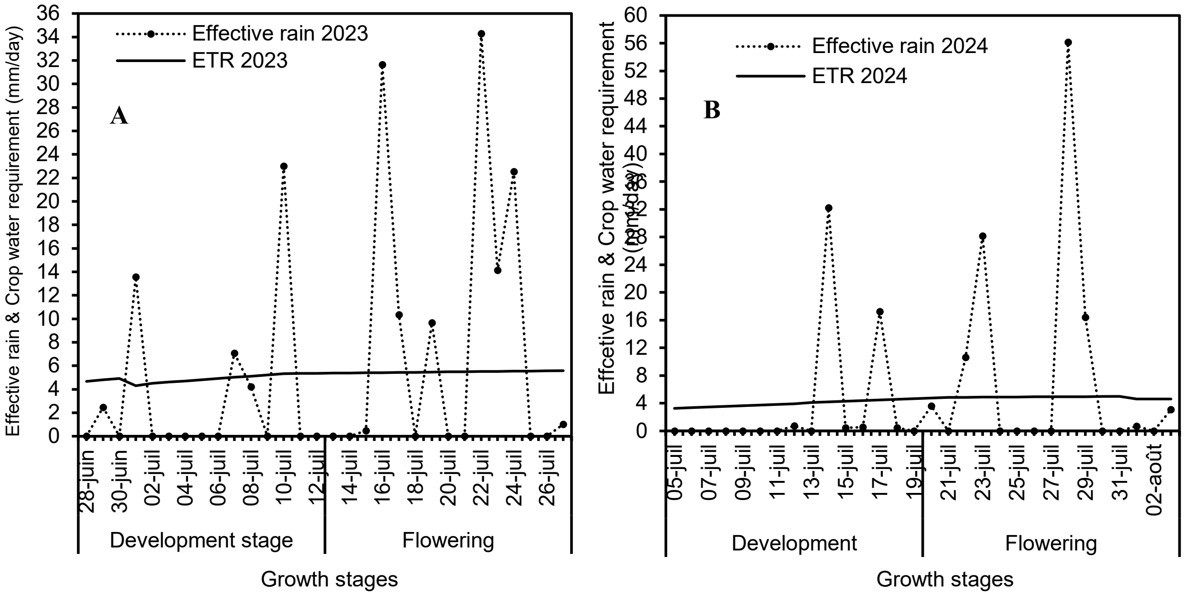

Fig. 2. Effective rain water and tomato water requirement during plant development and flowering stages in 2023 (A) and 2024 (B)

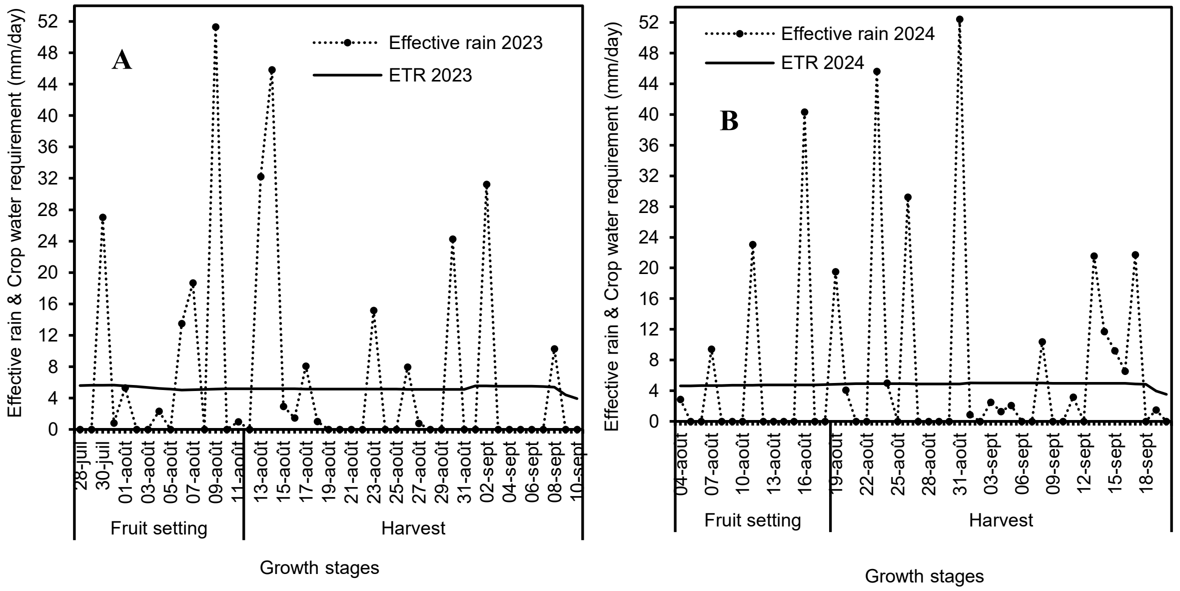

Fig. 3. Effective rain water and tomato water requirement during fruit setting stage and harvest in 2023 (A) and 2024 (B)

3.2 Effect of Treatments on Soil Microbial Respiration and Biomass

Irrigation water and urea management significantly affected microbial respiration and microbial biomass (Table 2). The trend in carbon dioxide (CO_2) released by respiration and the total mass of living microorganisms (microbial biomass) in the treatments indicated that all combinations outperformed the control. However, the highest values of these two parameters were obtained under PU + D75. Compared with the average of the other treatments, the application of pearled urea combined with 75% of tomato crop water requirement increased CO_2 release and microbial biomass by 152% and 145%, respectively.

Table 2. Effect of treatments on microbial respiration and biomass for 100 mg of soil

Treatments	Respiration (mg of CO_2/100 g of soil)	Microbial Biomass (mg/100 g of soil)
DPU + D100	22.66±0.25^{d}	22.57±0.83^{c}
DPU + D75	68.86±2.28^{b}	59.86±0.01^{a}
DPU + D50	31.53±1.44^{cd}	30.16±1.89^{b}
PU + D100	35.64±2.66^{c}	34.45±3.12^{b}
PU + D75	90.59±8.90^{a}	69.98±18.58^{a}
PU + D50	38.28±1.14^{c}	37.31±0.81^{b}
Control	18.40±0.51^{e}	18.39±0.07^{d}
P	0.0001	0.001
Significance	***	***

Legend: DPU+D100: deep placement of super granule urea+100% of tomato crop net irrigation depth; DPU+D75: deep placement of super granule urea+75% of tomato crop net irrigation depth; DPU+D50: deep placement of super granule urea+50% of tomato crop net irrigation depth. PU+D100: pearled urea+100% of tomato crop net irrigation depth; PU+D75: pearled urea+75% of tomato crop net irrigation depth; PU+D50: pearled urea+50% of tomato crop net irrigation depth.

***** Means within columns not followed by the same letter are significantly different at $p < 0.001$ level by Duncan's test; p Probability*

3.3 Effect of Treatments on Soil Organic Matter, Carbon and the Carbon/Nitrogen Ratio

The effects of water and urea management on soil organic matter (OM), carbon (C), and the carbon/nitrogen (C/N) ratio after two years are presented in Table 3. These parameters varied according to the combination of water and urea and were significantly different. The highest OM and C contents were obtained under PU + D75, followed by PU + D50, while the control exhibited the lowest values. Intermediate values were obtained in the other treatments. The application of PU + D75 enhanced soil OM and C contents by 210% and 215%, respectively, compared with the control, while increases of 76% were recorded for both OM and C contents compared with the average of the other treatments. For the C/N ratio, DPU + D50, PU + D100, and the control showed values lower than 10, indicating rapid decomposition of organic matter. In contrast, values higher than 10 were recorded under DPU + D100, DPU + D75, PU + D75, and PU + D50, indicating slow degradation of soil organic matter. The application of PU + D75 induced a C/N value of 12, which is required for ideal soil.

Table 3. Effect of treatments on soil organic matter, carbon and the ratio

Treatments	OM (%)	C (%)	C/N
DPU + D100	0.80±0.0057^{f}	0.46±0.00058^{f}	10±0.0057^{d}
DPU + D75	1.49±0.00058^{c}	0.86±0.00058^{c}	11±0.0057^{c}
DPU + D50	0.85±0.0057^{e}	0.49±0.00058^{e}	8±0.0057^{e}
PU + D100	1.44±0.00058^{d}	0.83±0.00058^{d}	8±0.0057^{e}
PU + D75	2.23±0.00058^{a}	1.29±0.00058^{a}	12±0.0057^{b}
PU + D50	1.76±0.00058^{b}	1.02±0.00058^{b}	13±0.0057^{a}
Control	0.72±0.00058^{g}	0.41±0.00058^{g}	8±0.0057^{e}
P	0.000	0.000	0.000
Significance	***	***	***

Legend: DPU+D100: deep placement of super granule urea+100% of tomato crop net irrigation depth; DPU+D75: deep placement of super granule urea+75% of tomato crop net irrigation depth; DPU+D50: deep placement of super granule urea+50% of tomato crop net irrigation depth. PU+D100: pearled urea+100% of tomato crop net irrigation depth; PU+D75: pearled urea+75% of tomato crop net irrigation depth; PU+D50: pearled urea+50% of tomato crop net irrigation depth.

**** Means within columns not followed by the same letter are significantly different at $p < 0.001$ level by Duncan's test; p Probability*

3.4 Effect of Treatments on Soil Nitrogen, Phosphorus and Potassium

The application of urea and irrigation water significantly influenced nitrogen (N), phosphorus (P), and potassium (K) dynamics in the soil (Table 4). Soil nutrients (NPK) varied according to the different combinations of water and urea. For N, most treatments produced higher values than the control, except DPU + D100, which underperformed. For P, DPU + D50, PU + D75, and PU + D50 produced lower values than the control. The application of DPU + D100, DPU + D50, PU + D100, and PU + D50 resulted in lower K contents than the control. DPU + D75 and PU + D75 showed higher values for these parameters. The highest N was observed under PU + D75, while the greatest P and K concentrations were identified under DPU + D75. The application of PU + D75 increased N content by 44%, while increases of 121% and 324% were obtained under DPU + D75 for P and K, respectively, compared with the average of the other treatments.

Table 4. Treatments effects on soil nitrogen, assimilable phosphorus and available potassium

Treatments	N (%)	P (mg/kg)	K (mg/kg)
DPU + D100	0.046±0.00058^{g}	12.02±0.0057^{d}	92.82±0.0057^{d}
DPU + D75	0.077±0.00058^{d}	22.18±0.0057^{a}	938.57±0.0057^{a}
DPU + D50	0.065±0.00058^{e}	7.36±0.0057^{f}	79.69±0.0057^{f}
PU + D100	0.0990±0.00058^{b}	13.89±0.0057^{b}	8.44±0.0057^{g}
PU + D75	0.10±0.00058^{a}	7.46±0.0057^{e}	917.94±0.0057^{b}
PU + D50	0.08±0.00058^{c}	6.01±0.0057^{g}	83.45±0.0057^{e}
Control	0.05±0.00058^{f}	13.58±0.0057^{c}	144.39±0.0057^{c}
P	0.000	0.000	0.000
Significance	***	***	***

Legend: DPU+D100: deep placement of super granule urea+100% of tomato crop net irrigation depth; DPU+D75: deep placement of super granule urea+75% of tomato crop net irrigation depth; DPU+D50: deep placement of super granule urea+50% of tomato crop net irrigation depth. PU+D100: pearled urea+100% of tomato crop net irrigation depth; PU+D75: pearled urea+75% of tomato crop net irrigation depth; PU+D50: pearled urea+50% of tomato crop net irrigation depth.
**** Means within columns not followed by the same letter are significantly different at p < 0.001 level by Duncan's test; p Probability.*

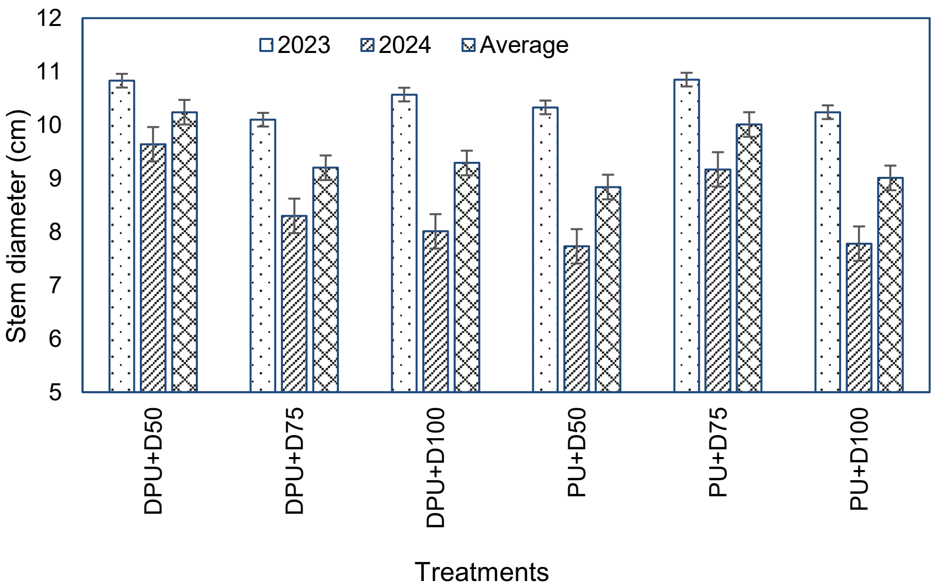

Fig. 4. Effect of treatments on tomato plant stem diameter

Legend: DPU+D100: deep placement of super granule urea+100% of tomato crop net irrigation depth; DPU+D75: deep placement of super granule urea+75% of tomato crop net irrigation depth; DPU+D50: deep placement of super granule urea+50% of tomato crop net irrigation depth. PU+D100: pearled urea+100% of tomato crop net irrigation depth; PU+D75: pearled urea+75% of tomato crop net irrigation depth; PU+D50: pearled urea+50% of tomato crop net irrigation depth

3.5 Treatment Effects on Growth Parameters

Fig. 4 illustrates the effects of water and urea management on tomato plant basal growth. The combinations of water and urea differently influenced stem diameter across 2023 and 2024. In 2023, no difference was observed among treatments; however, in 2024, the synergy between urea and water significantly affected girth, and the two-year average values differed significantly among treatments. Regression analysis indicated that stem diameter was year-dependent ($F = 111.19$, $P < 0.000$). The irrigation water regimes combined with urea types influenced plant growth over the two years. Higher and similar values were recorded under DPU + D50 and PU + D75. Increases of 13% and 10% were recorded for DPU + D50 and PU + D75, respectively, compared with the average of the other combinations.

3.6 Effects of Treatments on Tomato Yield

The effects of water-urea combinations on tomato yield were year-dependent (Fig. 5). In 2023, no significant difference was observed among treatments, whereas in 2024, the combinations significantly affected yield, and the two-year mean yield was notably affected. The absolute yield was approximately 14,090.38 t/ha, and the regression model showed that yield varied according to year ($F = 97.36$; $P < 0.001$). The highest production was recorded under PU + D75, with values statistically similar to those under DPU + D50 and DPU + D100. The lowest yields were recorded under DPU + D75 and PU + D50. On average, the application of PU + D75 increased yield by 34% compared with the average of the lower-performing treatments.

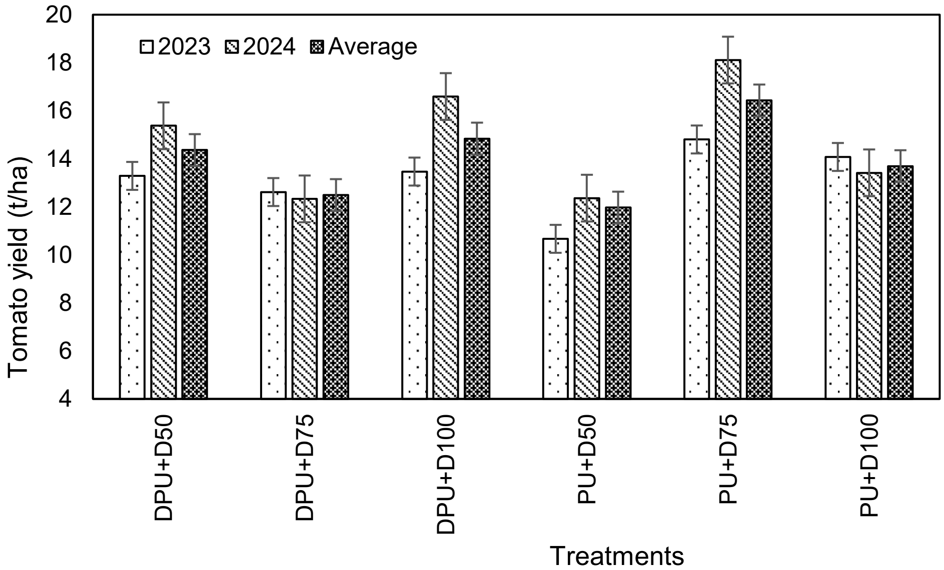

Fig. 5. Effect of treatments on tomato yield

Legend: DPU+D100: deep placement of super granule urea+100% of tomato crop net irrigation depth; DPU+D75: deep placement of super granule urea+75% of tomato crop net irrigation depth; DPU+D50: deep placement of super granule urea+50% of tomato crop net irrigation depth. PU+D100: pearled urea+100% of tomato crop net irrigation depth; PU+D75: pearled urea+75% of tomato crop net irrigation depth; PU+D50: pearled urea+50% of tomato crop net irrigation depth

3.7 Effects of Treatments on Water Productivity and Water Cost

The application of different combinations of water amount and urea significantly affected water-use efficiency and the water cost for producing 1 kg of tomato (Fig. 6). The two-year average values varied according to treatment. The highest water productivity was obtained under DPU + D50, while the lowest value was observed under PU + D100. The application of DPU + D50 increased water productivity by 107% while decreasing production cost by 66% compared with the lower-performing treatments.

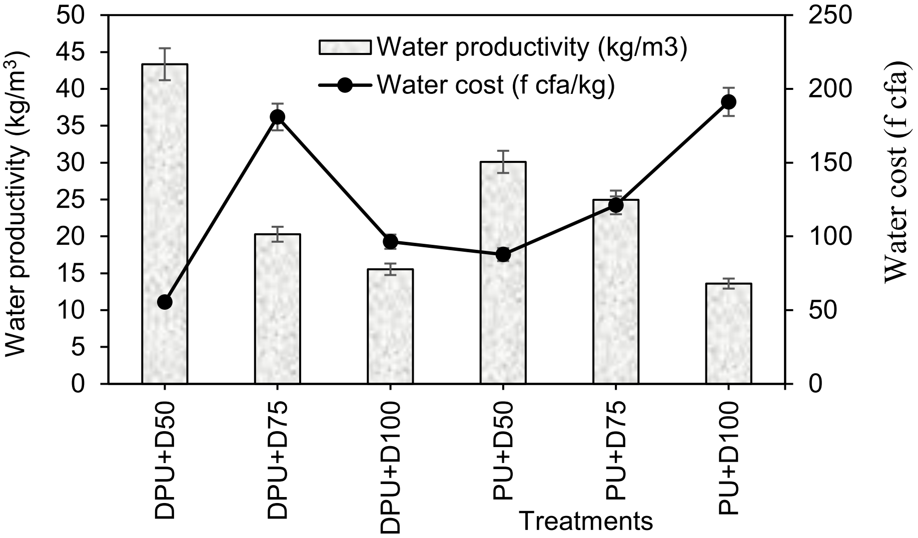

Fig. 6. Effect of treatments on water use efficiency and water cost

Legend: DPU+D100: deep placement of super granule urea+100% of tomato crop net irrigation depth; DPU+D75: deep placement of super granule urea+75% of tomato crop net irrigation depth; DPU+D50: deep placement of super granule urea+50% of tomato crop net irrigation depth. PU+D100: pearled urea+100% of tomato crop net irrigation depth; PU+D75: pearled urea+75% of tomato crop net irrigation depth; PU+D50: pearled urea+50% of tomato crop net irrigation depth

4. Discussion

In this study, different amounts of harvested water were combined with pearled urea and deep placement of urea by employing supplementary irrigation in the Sahel for tomato production. Synergistic effects were observed on soil microbial respiration and biomass, nutrient availability, plant growth, yield, and water productivity. Water efficiency, yield, and water cost were analysed to identify an optimal and sustainable combination that lowers production cost, maintains or improves soil fertility with limited yield penalty, and enhances water-use efficiency.

The findings revealed that microbial activity, including respiration and microbial biomass, was higher under the combination of pearled urea with irrigation water representing 75% of the tomato crop water requirement (PU + D75). The rapid release of N from pearled urea may have caused a rapid increase in microbial activity and biomass. The quick dissolution of nitrogen within a relatively short time, which led to the availability of a large amount of inorganic N, may have stimulated microorganism development. It is well known that the amount of inorganic nitrogen is important for soil microorganism activity and community structure. Microbes use inorganic nitrogen forms for metabolism, including the synthesis of proteins, DNA, and enzymes, as well as growth and reproduction that sustain microbial communities. Nitrogen is a critical energy source for microbes to build their biomass (Zuccarini *et al.*, 2023; He *et al.*, 2024; Geisseler *et al.*, 2014; Ali *et al.*, 2021; Zhang *et al.*, 2018). The abundance of nitrogen may therefore have increased the microorganism community involved in organic matter degradation (Fierer *et al.*, 2012; Ali *et al.*, 2021; Liu *et al.*, 2015; Tuo *et al.*, 2023). Initially, high available N stimulates microbial activity (He *et al.*, 2024; Geisseler *et al.*, 2014; Zhang *et al.*, 2018).

Microbial activity, including decomposition, nutrient cycling, and respiration, is also dependent on factors such as moisture. Irrigation at D75 appeared to provide an optimal amount of water that did not induce significant N-nutrient leaching, thereby creating favourable moisture conditions for microorganism development (Lei *et al.*, 2022; Rangel-Vasconcelos *et al.*, 2015; Siebielec *et al.*, 2020). The rapid solubility of pearled urea matched the D75 irrigation water amount, and this combination created favourable water and nutrient conditions for the expansion of the microbial community during organic matter decomposition, leading to a greater release of CO_2 and microbial biomass (Tuo *et al.*, 2023; Friedel *et al.*, 2000; Siebielec *et al.*, 2020).

Under the well-watered and sufficient inorganic N-availability conditions induced by PU + D75, microorganisms actively broke down material, increasing soil organic matter and carbon and transforming organic matter into N nutrients. The C/N ratio of 12 indicated the availability of high nutrients (Tuo *et al.*, 2023; Liu *et al.*, 2015).

The availability of a high amount of nitrogen released by microorganisms under the PU + D75 treatment may have stimulated greater N uptake by plants, a process that requires the consumption of both P and K. While nitrogen supports organic matter accumulation, stimulates growth, and enhances yield, P and K are required to support nitrogen-use efficiency at an optimal N:P:K ratio. P and K work together to accelerate N intake by plant roots. P and K are vital for maximising nitrogen uptake and metabolism in plants because they are involved in energetic and physiological processes. Phosphorus enhances N uptake, whereas potassium activates enzymes and aids translocation, making the combination more effective (Zuccarini *et al.*, 2023; You *et al.*, 2025; Liu *et al.*, 2015). P reinforces the root system to enhance N assimilation, while K facilitates N transfer to shoots and protein synthesis. P supports the production of adenosine triphosphate (ATP), which provides the energy needed for N uptake, reduction, and translocation. K is involved in the transport of absorbed N from roots to shoots and its subsequent conversion into proteins. K also helps regulate osmotic balance, charge balance, and transmembrane phloem loading. It is crucial for balancing the negative charge of nitrate (NO_3^-) as it is taken up by roots (Eurofins AgroScience, 2024; Siebielec *et al.*, 2020). Under high nitrogen content, plants intensify N absorption, inducing the consumption of phosphorus and potassium and leading to a decrease in these nutrients under PU + D75, although potassium was not drastically affected. K generally has a sharper and more immediate influence on N intake and assimilation by plants than phosphorus. K activates nitrate reductase, supports the conversion of absorbed nitrate, contributes to protein synthesis, and transports nitrate from roots to shoots. In a high-N context, microorganisms may have released more potassium, maintaining a relatively high K level in the soil. The increased N level stimulated microbial activity, resulting in higher turnover and greater production of organic acids that solubilised K (Eurofins AgroScience, 2024; Siebielec *et al.*, 2020). However, a high level of nitrogen can sometimes reduce the overall availability of phosphorus in the soil. Microbes respond to excessive N in soil by accelerating the mineralisation of labile organic P pools (He *et al.*, 2024; Liu *et al.*, 2015; Zhang *et al.*, 2018).

The highest values of phosphorus and potassium were obtained under the DPU + D75 combination. The slow release of nitrogen under the application of deep placement of granule urea combined with the optimal water depth of D75 increased P and K levels in the soil. The extended release of nitrogen may have induced gradual and slow N consumption by plants, a process that matched the slow release and utilisation of phosphorus and potassium (Ali *et al.*, 2021; Friedel *et al.*, 2000; Soretire *et al.*, 2019). The steady supply of nitrogen through DPU synchronised release and utilisation and extended the period during which P and K nutrients were available in the soil, leading to greater remaining amounts of these nutrients (Ali *et al.*, 2021; Friedel *et al.*, 2000; Soretire *et al.*, 2019). The controlled release of urea under DPU may also have decreased nutrient losses and enhanced the P and K status of the soil (Ali *et al.*, 2021; Friedel *et al.*, 2000; Soretire *et al.*, 2019).

Overall, the application of DPU + D50 and PU + D75 improved growth parameters such as stem diameter. Similar and higher values were obtained under these two treatments. Deep placement of granule urea matched irrigation water representing 50% of tomato water requirement, while pearled urea coincided with 75% of the water required by tomato crop. The combinations of DPU + D50 and PU + D75 made sufficient nitrogen available in the soil solution, coinciding with tomato plant needs and positively influencing growth. The effectiveness of urea types depended on the applied amount of water, which solubilises fertiliser according to its form and makes nitrogen available. The D50 and D75 irrigation water amounts probably created favourable moisture conditions that reduced nitrogen losses through leaching, leading to adequate N assimilation by plants for proper growth under DPU and PU, respectively. An appropriate nitrogen-water ratio synchronised with plant absorption rate increases nitrogen-use efficiency and enhances growth. The amount of available nitrogen strongly depends on release duration and the water amount, which should match plant uptake rate to reduce losses (Geisseler *et al.*, 2014; Lei *et al.*, 2022; Siebielec *et al.*, 2020).

Regarding yield, the highest value was obtained under PU + D75. Since the PU + D75 combination improved microbial activity and development, OM, C, N availability, plant growth, and the C/N ratio, it consequently increased tomato yield. The water conditions and adequate nutrient availability created by PU + D75 were suitable for tomato production (Geisseler *et al.*, 2014; Tuo *et al.*, 2023; Lei *et al.*, 2022).

However, treatment effects were not observed during the first year of the experiment in 2023. The different combinations did not affect tomato development and production in 2023, whereas plant growth and yield were affected in 2024. The short dry spells observed in 2023, due to favourable rainwater distribution during plant development, may have inhibited the effect of the different combinations. In contrast, the long dry spells observed during plant development in 2024 revealed the effect of water fluctuation combined with urea. Since dry spells were 30% and 50% longer at the development and flowering stages, respectively, in 2024, the impact of the different combinations on tomato growth and production was expressed. During the sensitive flowering and fruit-setting stages, tomato crops were subjected to prolonged and relatively sharper drought in 2024, while dry spell intensity and amplitude were lower in 2023 (Engelhardt *et al.*, 2018; Siebielec *et al.*, 2020).

Regarding water consumption, the highest productivity (43.34 kg/m^3) and the lowest water cost (55.52 F CFA/kg) were obtained under DPU + D50, which appeared to be the more profitable combination. This indicates that production peaked with a water volume of 1 m^3. The application of deep placement of urea with half of the tomato water requirement when implementing a rainwater harvesting technique resulted in the lowest water charges, with negligible yield penalty, and appeared more beneficial (Tuo *et al.*, 2023; Soretire *et al.*, 2019; Engelhardt *et al.*, 2018).

5. Conclusion

The study showed that the performance of supplementary irrigation using harvested rainwater depended on the interaction between irrigation depth and urea form. Pearled urea combined with 75% of tomato net irrigation requirement improved soil biological activity, organic matter, carbon, nitrogen, stem growth, and tomato yield. This treatment produced the highest average tomato yield among the evaluated combinations. Deep placement of super granule urea combined with 75% irrigation depth increased soil phosphorus and potassium contents, indicating a positive effect on selected soil nutrient parameters. In contrast, deep placement of super granule urea combined with 50% irrigation depth produced the highest water productivity and the lowest water cost per kilogram of tomato, suggesting its potential value under water-scarce conditions. These findings indicate that PU + D75 may be more suitable where the objective is to improve soil fertility and yield, while DPU + D50 may be more appropriate where water saving is the priority. The recommendations should be interpreted cautiously because the study was conducted at one location over two years. Longer-term trials, additional sites, and a full cost-benefit analysis are needed before broad recommendations can be made.

6. Limitations

This study was conducted at one experimental site over two cropping seasons; therefore, the results may be influenced by local soil conditions, rainfall distribution, and management practices. Only one tomato variety and a limited set of irrigation depths and urea forms were evaluated. The study did not include long-term monitoring of soil fertility, nutrient leaching, nitrogen-use efficiency, or residual effects after repeated cropping. Economic conclusions are also limited because a full cost-benefit analysis was not conducted. Future research should include multi-location trials, longer monitoring periods, detailed water balance, nutrient uptake, leaching assessment, and farm-level economic analysis.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s)

acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Adams, W. R., & Zeleke, K. T. (2017). Diurnal effects on the efficiency of drip irrigation. *Irrigation Science, 35*, 141–157. https://doi.org/10.1007/s00271-016-0529-1

Africa Rice Center. (2007). *Africa rice trends: Overview of recent developments in the Sub-Saharan Africa rice sector*.

Ali, S., Liu, K., Ahmed, W., Jing, H., Qaswar, M., Kofi Anthonio, C., Maitlo, A. A., Lu, Z., Liu, L., & Zhang, H. (2021). Nitrogen mineralization, soil microbial biomass and extracellular enzyme activities regulated by long-term N fertilizer inputs: A comparison study from upland and paddy soils in a red soil region of China. *Agronomy, 11*(10), Article 2057. https://doi.org/10.3390/agronomy11102057

Araya, M. J., Araya-Moreno, J., Coulibaly, Y. M., & Savadogo, T. B. (2024). Between 'the technical' and 'the social'? The case of farm ponds for supplemental irrigation in Burkina Faso and Mali. *International Journal of Rural Management*. https://doi.org/10.1177/09730052231221332

Barbier, B., Zongo, B., Dugué, P., & Zangré, B. V. C. A. (2015). L'irrigation de complément à partir de petits bassins individuels : Synthèse des travaux réalisés au Burkina Faso. *AGRIDAPE, 31*, 9–11. https://orbi.uliege.be/handle/2268/191924

Begna, T. (2020). Major challenging constraints to crop production farming system and possible breeding to overcome the constraints. *International Journal of Research Studies in Agricultural Sciences, 6*(7), 27–46. https://doi.org/10.20431/2454-6224.0607005

Bekele, T., Abebo, M., & Wabala, K. (2019). Evaluation of potato responses to supplementary irrigation in rain-fed agriculture at Misrak Azernet Berbere Woreda, Ethiopia. *Irrigation & Drainage Systems Engineering, 8*(2), 1–5. https://www.hilarispublisher.com/abstract/evaluation-of-potato-responses-to-supplementary-irrigation-in-rainfed-agriculture-at-misrak-azernet-berbere-woreda-ethio-22060.html

Domullodzhanov, D., & Rahmatilloev, R. (2023). Development of low-cost rainwater harvesting to support on-site water supply in rural Tajikistan. *Central Asian Journal of Water Research, 9*(2), 103–120. https://doi.org/10.29258/CAJWR/2023-R1.v9-2/103-120.eng

Engelhardt, I. C., Welty-Bernard, A., Blazewicz, S. J., Bru, D., Rouard, N., Breuil, M.-C., Gessler, A., Galiano, L., Miranda, J. C., Spor, A., & Barnard, R. L. (2018). Depth matters: Effects of precipitation regime on soil microbial activity upon rewetting of a plant-soil system. *The ISME Journal, 12*, 1061–1071. https://doi.org/10.1038/s41396-018-0079-z

Eurofins AgroScience. (2024). *Soil microbial biomass*. Eurofins Sac Ky Hai Dang. https://cdnmedia.eurofins.com/apac/media/k3hjvnex/soil-microbial-biomass.pdf

Faye, B., Sow, S., Fall, M. D., & Wade, B. (2020). Les performances agro-économiques de l'urée super granulé : Cas du riz au Sénégal. *European Scientific Journal, ESJ, 16*(13), 364. https://doi.org/10.19044/esj.2020.v16n13p364

Fierer, N., Lauber, C. L., Ramirez, K. S., Zaneveld, J., Bradford, M. A., & Knight, R. (2012). Comparative metagenomic, phylogenetic and physiological analyses of soil microbial communities across nitrogen gradients. *The ISME Journal, 6*, 1007–1017. https://doi.org/10.1038/ismej.2011.159

Fossi, S., Da Silveira, S., & Kokole, K. (2013). Design and implementation of runoff harvesting basins for supplemental irrigation in the Burkinabe Sahel. *Proceedings of the 1st World Irrigation Forum*. https://hdl.handle.net/10625/52227

Fox, P., & Rockström, J. (2003). Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel. *Agricultural Water Management, 61*(1), 29–50. https://doi.org/10.1016/S0378-3774(03)00008-8

Friedel, J. K., Langer, T., Siebe, C., & Stahr, K. (2000). Effects of long-term wastewater irrigation on soil organic matter, soil microbial biomass and its activities in central Mexico. *Biology and Fertility of Soils, 31*(5), 414–421. https://doi.org/10.1007/s003749900188

Geerts, S., & Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximise crop water productivity in dry areas. *Agricultural Water Management, 96*(9), 1275–1284. https://doi.org/10.1016/j.agwat.2009.04.009

Geisseler, D., & Scow, K. M. (2014). Long-term effects of mineral fertilizers on soil microorganisms—A review. Soil Biology and Biochemistry, 75, 54–63. https://doi.org/10.1016/j.soilbio.2014.03.023

He, C., Ruan, Y., & Jia, Z. (2024). Effects of nitrogen addition on soil microbial biomass: A meta-analysis. *Agriculture, 14*(9), Article 1616. https://doi.org/10.3390/agriculture14091616

Jadhav, S., Kamble, S., Patil, S., Raut, D., & Shende, S. (2026). Deficit irrigation and precision water management: Climate-smart strategies for sustainable agriculture. *Journal of Experimental Agriculture International, 48*(5), 610–625. https://doi.org/10.9734/jeai/2026/v48i54254

Jenkinson, D. S., & Powlson, D. S. (1976). The effects of biocidal treatments on metabolism in soil—V. A method for measuring soil biomass. *Soil Biology and Biochemistry, 8*(3), 209–213. https://doi.org/10.1016/0038-0717(76)90005-5

Kaboré, T. V. R., Keïta, A., Gana, A. L., Niang, D., & Boubé, B. (2024). Analysis of farmers' perceptions on sealing techniques for runoff harvesting ponds: A case study from Burkina Faso. *Resources, 13*(10), Article 144. https://doi.org/10.3390/resources13100144

Kambou, D., Xanthoulis, D., Ouattara, K., & Degré, A. (2014). Concepts d'efficience et de productivité de l'eau (synthèse bibliographique). *Biotechnologie, Agronomie, Société et Environnement, 18*(1), 108–120. https://hdl.handle.net/2268/162650

Kima, A. S., Chung, W.-G., Wang, Y.-M., & Traoré, S. (2015). Evaluating water depths for high water productivity in irrigated lowland rice field by employing alternate wetting and drying technique under tropical climate conditions, Southern Taiwan. *Paddy and Water Environment, 13*(4), 379–389. https://doi.org/10.1007/s10333-014-0458-7

Kima, A. S., Gyamfi, C., Kima, E., Ouédraogo, C., Traoré, O., Wang, Y.-M., Traoré, S., & Sangaré, S. A. K. (2024). Evaluating dripper-plants spacing for improving tomato yield and water productivity under the drip-irrigation system in the Sudanian climate in Burkina Faso. *Journal of Irrigation and Drainage Engineering, 150*(2), Article 04024003. https://doi.org/10.1061/JIDEDH.IRENG-10172

Kima, A. S., Kima, E., Bacyé, B., Ouédraogo, P. A. W., Traoré, O., Traoré, S., Nandkangré, H., Chung, W.-G., & Wang, Y.-M. (2020). Evaluating supplementary water methodology with saturated soil irrigation for yield and water productivity improvement in semi-arid rainfed rice system, Burkina Faso. *Sustainability, 12*(12), Article 4819. https://doi.org/10.3390/su12124819

Kima, A. S., Sandwidi, B.-W. B., Gyamfi, C., Sangaré, S. A. K. B., Tougri, S., & Kima, E. (2025a). Exploring the possibility of utilizing surface water run-off and shallow groundwater for improving rice productivity in semi-arid climate of Burkina Faso. *EWASH & TI Journal, 9*(2), 1211–1220. https://revues.imist.ma/index.php/ewash-ti/article/view/55084

Kima, A. S., Yanogo, W. A. P., Sandwidi, B.-W. B., Kima, E., & Wang, Y.-M. (2025b). Evaluating supplementary irrigation depths for the improvement of water productivity and rice yield in semi-arid climate, Eastern Burkina Faso. *American Journal of Water Science and Engineering, 11*(3), 60–73. https://doi.org/10.11648/j.ajwse.20251103.12

Kjeldahl, J. (1883). Neue Methode zur Bestimmung des Stickstoffs in organischen Körpern. *Zeitschrift für Analytische Chemie, 22*, 366–382. https://doi.org/10.1007/BF01338151

Lei, H., Yu, J., Zang, M., Pan, H., Liu, X., Zhang, Z., & Du, J. (2022). Effects of water-fertilizer-air-coupling drip irrigation on soil health status: Soil aeration, enzyme activities and microbial biomass. *Agronomy, 12*(11), Article 2674. https://doi.org/10.3390/agronomy12112674

Liu, L., Gundersen, P., Zhang, W., Zhang, T., Chen, H., & Mo, J. (2015). Effects of nitrogen and phosphorus additions on soil microbial biomass and community structure in two reforested tropical forests. *Scientific Reports, 5*, Article 14378. https://doi.org/10.1038/srep14378

Mehla, M. K., & Singh, K. (2019). Optimizing drip irrigation system design for onion crop using DIDAS software. *Bulletin of Environment, Pharmacology and Life Sciences, 8*(2), 64–69. https://bepls.com/bepls_jan2019/13.pdf

Nangare, D. D., Singh, Y., Kumar, P. S., & Minhas, P. S. (2016). Growth, fruit yield and quality of tomato (*Lycopersicon esculentum* Mill.) as affected by deficit irrigation regulated on phenological basis. *Agricultural Water Management, 171*, 73–79. https://doi.org/10.1016/j.agwat.2016.03.016

Ogbiye, A. S., Fagbenle, E., Busari, A. A., Onakunle, O. O., & Omole, D. O. (2021). Rain water harvesting: A sustainable alternative for domestic water supply in South-Western Nigeria: In the case study of Ado-Odo/Ota LGA Ogun State. *IOP Conference Series: Materials Science and Engineering, 1036*(1), Article 012002. https://doi.org/10.1088/1757-899X/1036/1/012002

Ouedraogo, R., Montginoul, M., & Barbier, B. (2024). Farmers' behavior and innovations' adoption processes in rural Sahel: Case of supplemental irrigation from farm ponds in Burkina Faso. *The Journal of Rural and Community Development, 19*(2), 80–104. https://journals.brandonu.ca/jrcd/article/view/2328

Raimondi, A., Quinn, R., Abhijith, G. R., Becciu, G., & Ostfeld, A. (2023). Rainwater harvesting and treatment: State of the art and perspectives. *Water, 15*(8), Article 1518. https://doi.org/10.3390/w15081518

Rangel-Vasconcelos, L. G. T., Zarin, D. J., Oliveira, F. de A., Vasconcelos, S. S., Carvalho, C. J. R. de, & Santos, M. M. de L. S. (2015). Effect of water availability on soil microbial biomass in secondary forest in Eastern Amazonia. *Revista Brasileira de Ciência do Solo, 39*(2), 377–384. https://doi.org/10.1590/01000683rbcs20140135

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., & Gerten, D. (2009). Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research, 45*, Article W00A12. https://doi.org/10.1029/2007WR006767

Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., & Qiang, Z. (2010). Managing water in rainfed agriculture—The need for a paradigm shift. *Agricultural Water Management, 97*(4), 543–550. https://doi.org/10.1016/j.agwat.2009.09.009

Sanfo, S., Barbier, B., Dabiré, I. W.-P., Vlek, P. L. G., Fonta, W. M., Ibrahim, B., & Barry, B. (2017). Rainfall variability adaptation strategies: An ex-ante assessment of supplemental irrigation from farm ponds in southern Burkina Faso. *Agricultural Systems, 152*, 80–89. https://doi.org/10.1016/j.agsy.2016.12.011

Sanogo, M., Yonaba, R., Lawane, A., Zorom, M., Tassembédo, F., Sahad, H. A., & Bazié, I. (2024). Do runoff water harvesting ponds affect farmers' cropping choices? Insights from smallholders in the West African Sahel. *Sustainability, 16*(18), Article 8000. https://doi.org/10.3390/su16188000

Siebielec, S., Siebielec, G., Gałązka, A., Grządziel, J., Klimkowicz-Pawlas, A., & Stuczyński, T. (2020). Impact of water stress on microbial community and activity in sandy and loamy soils. *Agronomy, 10*(9), Article 1429. https://doi.org/10.3390/agronomy10091429

Soretire, A. A., Sakariyawo, O. S., Yewande, O. S., Adesodun, J. K., Akintokun, A. K., Soremi, P. A. S., & Aderibigbe, S. G. (2019). Changes in microbial biomass and grain yield of rice varieties in response to the alternate wet and dry water regime in the inland valley of derived savanna. *Journal of Agricultural Sciences, 64*(3), 239–253. https://doi.org/10.2298/JAS1903239S

Tessema, I., & Simane, B. (2021). Smallholder farmers' perception and adaptation to climate variability and change in Fincha'a sub-basin of the Upper Blue Nile River Basin of Ethiopia. *GeoJournal, 86*(4), 1767–1783. https://doi.org/10.1007/s10708-020-10159-7

Traoré, H., Barro, A., Yonli, D., Stewart, Z., & Prasad, V. (2020). Water conservation methods and cropping systems for increased productivity and economic resilience in Burkina Faso. *Water, 12*(4), Article 976. https://doi.org/10.3390/w12040976

Traore, O., Traore, S., Wang, Y.-M., & Kima, A. S. (2016a). Local community's adaptive strategies to drought in the Sahel zone of Burkina Faso. *International Journal of Sciences: Basic and Applied Research, 28*(3), 50–64. https://www.gssrr.org/JournalOfBasicAndApplied/article/download/6046/2973/16744

Traore, O., Traore, S., Wang, Y.-M., & Kima, A. S. A. (2016b). A preliminary assessment of climate impact on cotton production in semiarid zone of Africa: Case study of Burkina Faso. *Imperial Journal of Interdisciplinary Research, 2*, 1450–1455. https://fps.npust.edu.tw/en/biblio/A%20Preliminary%20Assessment%20of%20Climate%20Impact%20on%20Cotton%20Production%20in%20Semiarid%20Zone%20of%20Africa%3A%20Case%20study%20of%20Burkina%EF%BF%BD3146b1ab43107671034/

Tuo, Y., Wang, Z., Zheng, Y., Shi, X., Liu, X., Ding, M., & Yang, Q. (2023). Effect of water and fertilizer regulation on the soil microbial biomass carbon and nitrogen, enzyme activity, and saponin content of *Panax notoginseng*. *Agricultural Water Management, 278*, Article 108145. https://doi.org/10.1016/j.agwat.2023.108145

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science, 37*(1), 29–38. https://doi.org/10.1097/00010694-193401000-00003

Wallace, J. S. (2000). Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems & Environment, 82*(1–3), 105–119. https://doi.org/10.1016/S0167-8809(00)00220-6

Xu, J., Li, X., Wan, W., Zhu, X., Li, C., Zhao, X., Zhao, Y., Pang, S., & Diao, M. (2024). Impact of regulated deficit irrigation on the dynamics of quality changes in processing tomato fruits during ripening. *Agricultural Water Management, 304*, Article 109068. https://doi.org/10.1016/j.agwat.2024.109068

Yameogo, P. L. (2009). *Contribution des granules d'urée dans l'amélioration des rendements : Cas de la Vallée du Kou au Burkina Faso* [Mémoire d'ingénieur agronome, Université Polytechnique de Bobo-Dioulasso].

Yameogo, P. L., Traoré, A., & Arzouma, B. A. (2021). Influence des modes de gestion de l'eau et de la fumure minérale sur quelques paramètres chimiques du sol et le rendement du riz à la Vallée du Kou au Burkina Faso. *Journal of Applied Biosciences, 165*, 17099–17110.

Yao, Y., Zhang, M., Tian, Y., Zhao, M., Zhang, B., Zhao, M., Zeng, K., & Yin, B. (2018). Urea deep placement for minimizing NH_3 loss in an intensive rice cropping system. *Field Crops Research, 218*, 254–266. https://doi.org/10.1016/j.fcr.2017.03.013

You, M., Li, L.-J., Horwath, W. R., & Zhu-Barker, X. (2025). Linking changes in soil microbial biomass size and nitrogen availability to increased N_2O production. *Soil Science Society of America Journal, 89*, Article e70143. https://doi.org/10.1002/saj2.70143

Youngoke, S. A., Ejezie, C. E., Kusibu, M. M., & Owuala, V. C. (2026). Integrated soil-water-plant modeling to optimize fertilizer and irrigation use efficiency in smallholder farming systems: A mechanistic narrative review. *Journal of Global Agriculture and Ecology, 18*(3), 61–83. https://doi.org/10.56557/jogae/2026/v18i310739

Zhang, T., Chen, H. Y. H., & Ruan, H. (2018). Global negative effects of nitrogen deposition on soil microbes. *The ISME Journal, 12*(7), 1817–1825. https://doi.org/10.1038/s41396-018-0096-y

Zhao, M., Niu, D., Li, B., Pan, C., Yao, M., Mao, L., Xu, Z., Sun, L., & Gao, M. (2025). The comprehensive effects of water-nitrogen coupling regulation on energy-saving greenhouse tomato growth and water-nitrogen utilization. *Frontiers in Plant Science, 16*, Article 1644877. https://doi.org/10.3389/fpls.2025.1644877

Zongo, B., Diarra, A., Barbier, B., Zorom, M., Yacouba, H., & Dogot, T. (2015). Farmers' practices and willingness to adopt supplemental irrigation in Burkina Faso. *International Journal of Food and Agricultural Economics, 3*(1), 101–117. https://doi.org/10.22004/ag.econ.200129

Zuccarini, P., Asensio, D., Sardans, J., Ogaya, R., Liu, L., & Peñuelas, J. (2023). Effects of nitrogen deposition on soil enzymatic activity and soil microbial community in a Mediterranean holm oak forest. Geoderma, 430, Article 116354. https://doi.org/10.1016/j.geoderma.2023.116354

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