Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 14 July 2026
Revised 21 Aug 2026
Accepted 04 Sep 2026

Natural Resources for Human Health 2026, Vol. 6 (19s): 783–793

KEYWORDS:
Allium cepa L.; Benefit-Cost Ratio; Irrigation Water Productivity; Lean Agricultural Management; Partial Factor Productivity; Regulated Deficit Irrigation; Smart Foliar Fertilizer.

Effect of Smart Fertilizer Application Rates and Irrigation Levels on Onion Sustainability in Semi-Arid Regions

Marwan Musa Nasr[1], Hanan Salah Mahdee[2], Hussein Abbas Mohammed1 and Husian A. Isa[3]

[1]Dep. of Desertification Combat, College of Agricultural Eng. Sci., University of Baghdad, Baghdad, Iraq. 10071.
[2]Dept. of Soil Sciences and Water Resources, College of Agriculture, Kirkuk University, Kirkuk, Iraq. 36001.
[3]Dept. of Soil Sciences and Water Resources, College of Agricultural Eng. Sci., University of Baghdad, Baghdad, Iraq. 10071.
Emails:
marwan.m@coagri.uobaghdad.edu.iq
hussein.abbas@coagri.uobaghdad.edu.iq
hanansalah@uokirkuk.edu.iq
husain.a@coadec.uobaghdad.edu.iq

ABSTRACT: To optimize the productivity of water and nutrients in semi-arid environments with increasing climate stress, a timely shift towards lean precision management is needed. This study quantitatively evaluated the synergistic interaction between regulated deficit irrigation thresholds (35% [ ], 40% [ ], and 75% [ ] available soil moisture depletion) and smart foliar fertilization rates (0% [ ], 50% [ ], and 100% [ ] of the recommended dose) on a shallow-rooted onion (Allium cepa L.) crop in Kirkuk Governorate, Iraq. Hydro-physical analysis demonstrated that moderate deficit irrigation ( ) optimized the root-zone soil water characteristic curve, preventing non-productive deep percolation losses and maximizing Irrigation Water Productivity (IWP) to a peak mean of 25.69 compared to (23.51) and (16.98). Under severe soil matric stress ( ), exogenous application of full-dose smart fertilizer ( ) acted as a crucial physiological buffer; it physically bypassed drought-induced nutrient paralysis in the rhizosphere, restoring cellular turgor and recovering plant height to 52.00 cm compared to 29.33 cm in the unfertilized control ( ). Agronomic evaluation of the Partial Factor Productivity of fertilizer (PFP) strictly exhibited the Law of Diminishing Marginal Returns, where the half-dose ( ) achieved superior nutrient utilization efficiency (4791.67) over (2732.64). Crucially, the strategic bio-economic interaction coupling moderate moisture depletion with full-dose foliar nutrition ( ) epitomized lean management by minimizing gross hydrological inputs while sustaining high bulb yields, achieving the absolute highest variable Benefit-Cost Ratio (BCR) of 14.68. The results showed that the use of calculated deficit irrigation combined with smart targeted foliar application is an effective strategy to reduce hydraulic losses and generate maximum economical productivity from every water drop used in sensitive dryland areas.

1. INTRODUCTION

Climate change, even more short-term severe droughts, and unprecedented depletion of groundwater reserves are threatening the lives of global agricultural systems in semi-arid regions (Pokhrel *et al.*, 2021). Over 70% of the freshwater withdrawn from

the ground is utilized in agriculture, and if the balance between supply and demand is upset, desertification and salinization of soils result in irreversible loss of soil physical structure and fertility. (Hillel, 1998; FAO, 2022). This critical reality calls for a paradigm change from the absolute yield maximization approach that drains water resources to a more efficient use of water to guarantee ecosystem resilience and economic viability (Rosa *et al.*, 2020). This change is particularly important in onion (Allium cepa L.) which has a very shallow, fibrous root system limited to 0.3 to 0.6 meter (Weaver, 1926). Onions have a critical moisture depletion factor (p) of only 0.30, so they quickly become under drought stress, and as soon as they enter drought shock, they experience rapid stomatal closure, resulting in a dramatic decrease in gas exchange and photosynthesis, which can threaten bulb differentiation and sustainable yield (Allen *et al.*, 1998; Wakchaure *et al.*, 2018). Use of traditional chemical fertilizers can increase this vulnerability by leaching out during irrigation, or by causing osmotic "root paralysis" as soils dry, further limiting uptake of water and nutrients (Marschner, 2012). Hence, smart and nano-fertilizers are now a promising protective technology, providing controlled release of nutrients and enhanced foliar penetration that significantly minimises environmental losses (Cao *et al.*, 2025). These intelligent fertilizers are also a drought protection system because they improve the cellular regulation of osmotic water, which helps to reduce the accumulation of stress metabolites (Wei *et al.*, 2025), and because they condition the metabolism of plant leaves so that they are able to continue with maximal photosynthetic activity during periods of acute water stress (López-Vargas *et al.*, 2026). When these advanced nutritional tools are combined with controlled deficit irrigation (RDI), it is an important physiological synergy that redirects the focus from maintaining a level of crop yield to optimizing water use (Fereres & Soriano, 2007; Zahedi *et al.*, 2019; Dimkpa *et al.*, 2020). An important fundamental research need is to quantify this synergistic effect of different smart fertilizer application rates and different moisture depletion thresholds, especially within the biophysical and economic sustainability of shallow-rooted crops in semi-arid climates. To fill this gap, this study will assess the combined effect of different levels of fertilizer (rates) and water-stress thresholds on the hydro and physiological performance of onions, identify the fertilizer and irrigation combination that would maximize yield while minimizing inputs, and quantify the effects of water-use efficiency (WUE) and economic viability to ensure strong agroecological resilience over time.

2. MATERIALS AND METHODS

2.1. Study site, soil preparation, and planting

The field experiment took place in Kirkuk Governorate during the winter / spring period of agricultural farming in 2026. The experimental field was prepared mechanically in accordance with the regular agricultural practices, comprising site preparation, primary plowing and harrowing to break up the topsoil and provide uniform seedbed, as required for establishment of shallow-rooted crops, onions included (Hillel, 2004). A localised onion variety was planted on 5th January 2026. The standard planting geometry was used for uniform growth and to reduce competition for water and nutrients, and a planting density of 33 to 50 plants "m" ^(-2) was found to be optimal. Growth continued until physiological maturity (lodging of about 80% of vegetative tops) on April 28, 2026. All weed and pest control was done manually and chemically when necessary to avoid any confounding effects on the water stress treatments.

2.2. Soil physical and chemical properties

Representative soil samples were collected from the active root zone (0–30 cm depth) prior to the initiation of the experiment and at its conclusion to assess changes in physicochemical properties, following the protocols described by Dane and Topp (2002) and Sparks *et al.* (1996). The fundamental characteristics of the experimental soil are presented in Table 1. Mechanical analysis indicated a sandy clay loam (SCL) texture. Notably, at the end of the experiment, an improvement in soil properties was observed; bulk density and electrical conductivity (EC) decreased, whereas soil organic matter (SOM) and cation exchange capacity (CEC) increased.

Table 1: Physical and chemical properties of the experimental soil before and after the experiment

Soil Properties	Units	Initial	Final
Physical Properties			
Sand	$g\,kg^{-1}$	630	-----

Clay	$g\ kg^{-1}$	305	-----
Silt	$g\ kg^{-1}$	65	-----
Soil Texture	-----	*Sandy Clay Loam (SCL)*	*Sandy Clay Loam (SCL)*
Bulk Density	$Mg\ m^{-3}$	1.36	1.32
Particle Density	$Mg\ m^{-3}$	2.64	2.65
Hydro-Physical Properties			
Saturation Moisture Content (θ_{Sat})	$m^3\ m^{-3}$	0.485	0.502
Field Capacity (θ_{FC})	$m^3\ m^{-3}$	0.200	0.230
Permanent Wilting Point (θ_{PWP})	$m^3\ m^{-3}$	0.090	0.100
ChemicalProperties			
Organic Matter (SOM)	$g\ m^{-3}$	12.0	14.4
Cation Exchange Capacity (CEC)	$meq\ (100g)^{-1}$	18.0	24.0
Calcium Carbonate ($CaCO_3$)	$g\ kg^{-1}$	260	200
Electrical Conductivity (EC_e)	$dS\ m^{-1}$	3.86	3.30
pH	-----	7.6	7.4

2.3. Drip irrigation evaluation and experimental design

Before planting, the drip irrigation system was tested in the field to obtain the Distribution Uniformity (DU) coefficient, thus guaranteeing uniform distribution of water discharge among various experimental plots. (Camp, 1998). The experiment was laid out in a Randomized Complete Block Design (RCBD) with a factorial arrangement in three replications. The total experimental area of 500 m^2 was divided into 27 plots. The study involved two main factors: (i) water stress at three levels of available soil moisture depletion (35%, 40%, and 75%), and (ii) smart fertilizer application rates at three levels (0%, 50%, and 100% of the recommended dose).

2.4. Irrigation management and scheduling

Care was taken to control irrigation with perfect precision, three fundamental parameters being strictly observed: the method, the timing and the quantity. Water was supplied through a very uniform surface drip irrigation system, which allowed localised water supply directly to the active root zone (0-30 cm depth) to minimise direct evaporation losses from the soil surface and prevent surface runoff. The Total Available Water (TAW, mm) in the root zone was fundamentally computed based on the initial volumetric soil water content boundaries (Allen *et al.*, 1998; Hillel, 2004):

$$TAW = (\theta_{FC} - \theta_{PWP}) \times Z_r$$

where θ_{FC} and θ_{PWP} represent the initial volumetric soil moisture content ($m^3\ m^{-3}$) at field capacity (0.200 $m^3\ m^{-3}$) and permanent wilting point (0.090 $m^3\ m^{-3}$), respectively, and Z_r is the effective rooting depth (300 mm). The baseline TAW was established at 33.0 mm. Irrigation timing was triggered exclusively when the predefined moisture depletion fractions (f) —35% (W_1), 40% (W_2), and 75% (W_3) of the TAW— were reached. The net irrigation requirement (I_{net}, mm) was calculated as:

$$I_{net} = f \times TAW = (\theta_{FC} - \theta_i) \times Z_r$$

where θ_i is the actual volumetric soil moisture content ($m^3\ m^{-3}$) immediately prior to irrigation. The gross applied irrigation depth (I_{gross}, mm) was volumetrically adjusted utilizing the previously determined DU:

$$I_{gross} = \frac{I_{net}}{DU}$$

Throughout the growing season, the cumulative gross applied irrigation volumes (I_w) were 748.8 $m^3\ ha^{-1}$, 641.9 $m^3\ ha^{-1}$, and 802.3 $m^3\ ha^{-1}$ for the 35%, 40%, and 75% depletion treatments, respectively.

2.5. Basal fertilization and smart foliar application

Basal fertilizers were soil-applied according to standard recommendations for onions. For the smart fertilizer treatments, "LOVO" fertilizer was applied as a foliar spray to bypass the challenges of chemical fixation in alkaline soils. The applied spray volume was 1600 $L\ ha^{-1}$. The smart fertilizer was applied at concentrations of 4 $g\ L^{-1}$ for the full recommendation (100%, generating an applied dry mass of 6.4 $kg\ ha^{-1}$) and 2 $g\ L^{-1}$ for the half recommendation (50%, generating 3.2 $kg\ ha^{-1}$), with the control receiving distilled water. Applications were timed according to the BBCH scale (leaf development BBCH 10-19; bulb formation BBCH 41-49) to maximize stomatal absorption (Meier, 2001).

2.6. Vegetative Growth Parameters

Morphological indicators were collected at physiological maturity to assess the physiological reaction and the canopy development under two soil moisture stress and three foliar nutrient stress. A random and representative sample of plants was taken from each of the experimental plots and plant height (cm) and number of functional leaves/plant were measured.

2.7. Irrigation Water Productivity (IWP)

To evaluate the engineering and physical efficiency of the irrigation system in converting applied water into economic biomass, the Irrigation Water Productivity ($IWP, kg\ m^{-3}$) was calculated (Ali & Talukder, 2008):

$$IWP = \frac{Y}{I_w}$$

where Y is the economic bulb yield ($kg\ ha^{-1}$) and I_w is the cumulative gross applied irrigation volume ($m^3\ ha^{-1}$).

2.8. Partial Factor Productivity of Fertilizer (PFP)

The Partial Factor Productivity of Fertilizer (PFPF) has been calculated.Partial Factor Productivity of Fertilizer (PFPF) has been determined. ($PFP, kg\ kg^{-1}$) was evaluated for the fertilized treatments (Dobermann, 2007):

$$PFP = \frac{Y}{F_a}$$

where Y is the economic bulb yield ($kg\ ha^{-1}$), and F_a is the total dry mass of the applied smart fertilizer ($kg\ ha^{-1}$).

2.9. Economic Sustainability and Benefit-Cost Ratio (BCR)

To determine the most sustainable and "lean" agricultural practice that maximizes value while minimizing financial waste, the variable Benefit-Cost Ratio (BCR) was computed (Gittinger, 1982). Based on local Iraqi market prices (1 USD = 1320 IQD), the farm-gate price of onions was 0.57 $USD\ kg^{-1}$. The total variable costs included the cost of irrigation water (1.00 $USD\ m^{-3}$) and the smart fertilizer cost (36.36 $USD\ ha^{-1}$ for F_2, and 18.18 $USD\ ha^{-1}$ for F_1).

Natural Resources for Human Health
eISSN: 2583-1194

$$BCR = \frac{\text{Total Gross Return}}{\text{Total Variable Cost}}$$

2.10. Statistical analysis and Data Visualization

The obtained data were subjected to Analysis of Variance (ANOVA) appropriate for a Randomized Complete Block Design (RCBD) with a factorial arrangement. All statistical computing and high-resolution data visualizations (350 DPI) were fundamentally executed using the Python programming language (Python Software Foundation). Specifically, the pandas library was utilized for dataset structuring, statsmodels for ANOVA and Least Significant Difference (LSD) modeling at $P \leq 0.05$, and seaborn alongside matplotlib for generating publication-ready graphical representations.

3.1. Vegetative Growth Parameters: Bio-physical Responses

The vegetative growth indicators showed a very complex dynamic response, predominantly determined by the soil moisture energy status and exogenous nutrient supply (Figures 1 and 2). The main effects analysis revealed that as the dryness of the soil increased from 35% (W_1) to 75% (W_3), there was a significant decrease in the number of functional leaves from 23.11 to 18.44, and the mean plant height decreased from 54.89 cm to 41.89 cm (Figure 1). (Figure 2). The soil physics explanation of this developmental suppression, from a mechanistically standpoint, is due to the approach of the volumetric water content (θ) to the permanent wilting point of the soil. At this critical threshold, the soil matric potential (ψ_m) drops exponentially, and the unsaturated hydraulic conductivity ($K(\theta)$) severely deteriorates. This hydraulic restriction severely limits the mass flow of water toward the rhizosphere, precipitating a collapse in cellular turgor pressure (ψ_p)— the main hydraulic force that causes cell elongation and cell division, as well as activating defense mechanisms and stomatal closure in cells. (Shock & Wang, 2011).

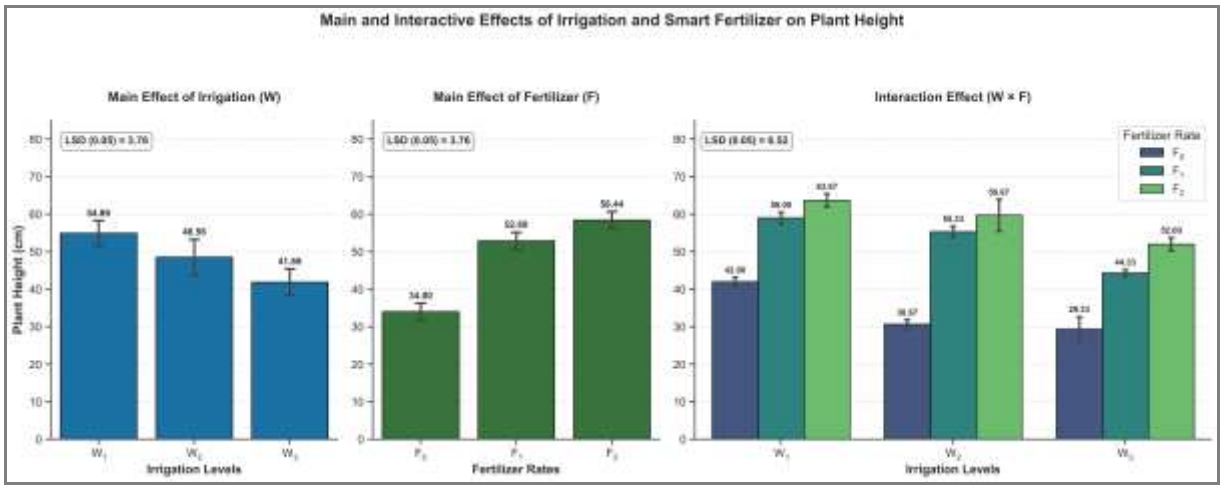


Figure 1: Main and interactive effects of soil moisture depletion thresholds (W) and smart foliar fertilizer rates (F) on plant height (cm). The error bars represent the standard error (SE) of the means, and text boxes indicate the Least Significant Difference (LSD) at $P \leq 0.05$.

Natural Resources for Human Health
eISSN: 2583-1194

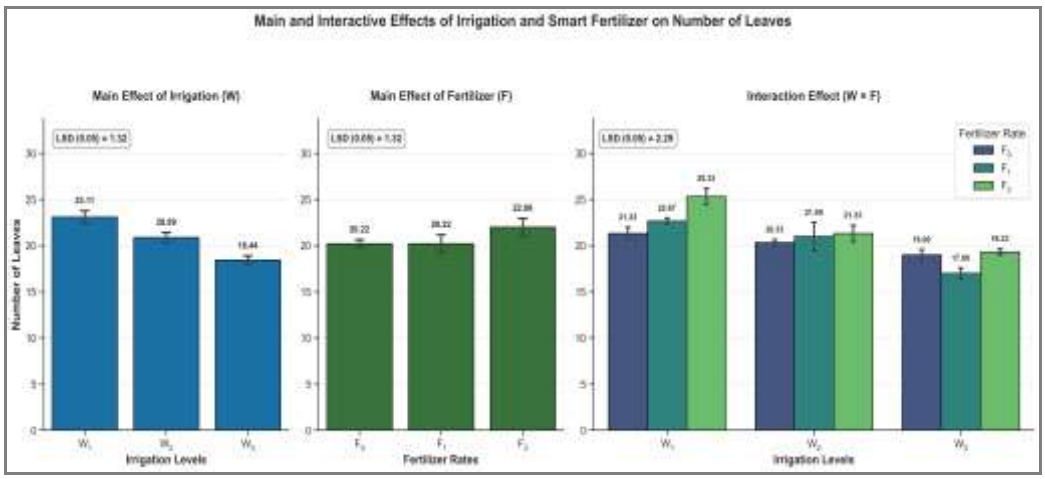


Figure 2: Main and interactive effects of soil moisture depletion thresholds (W) and smart foliar fertilizer rates (F) on the number of functional leaves per plant. The error bars represent the standard error (SE) of the means, and text boxes indicate the Least Significant Difference (LSD) at $P \leq 0.05$.

However, the interaction analysis ($W \times F$) unveiled a highly critical compensatory mechanism that highlights the bio-economic resilience of the system. Under severe water stress conditions (W_3), In the case of the unfertilised control (F_0)), there was a collapse in structure, with a plant height of 29.33 cm only (Figure 1)). The bio-physical intervention was through the use of the full dose smart foliar fertilizer, which is remarkable. (F_2) under this exact severe drought stress (W_3) led to a significant physiological recovery, restoring plant height to 52.00 cm (Figure 1) and stabilizing the leaf count at 19.33 (Figure 2). The significant recovery shows that providing exogenous nutrients through the plant's stoma is successful in overcoming the drought-induced "nutrient paralysis" and elemental immobilization that occurs in the dry soil solution. (Fernández & Brown, 2013). The foliar nutrient supply improved the efficiency of osmoregulation in guard cells, which resulted in stomatal conductance and assimilation of structural biomass remaining constant when water readily available in the root zone was drastically reduced. (Bekele & Tilahun, 2007; Wang *et al.*, 2013).

3.2. Irrigation Water Productivity (IWP): Hydrological and Agronomic Efficiency

Irrigation Water Productivity (IWP) was highly sensitive and showed a critical hydrological dynamic linked with the engineering efficiency of the irrigation water management (Figure 3). The main effects were analyzed to check the effect of the moderate regulated deficit irrigation regime. (W_2, 40% depletion) achieved the peak engineering efficiency, recording the highest mean IWP (25.69 kg m-3), which significantly outperformed the well-irrigated treatment (W_1, 35% depletion) that recorded 23.51 kg m-3.

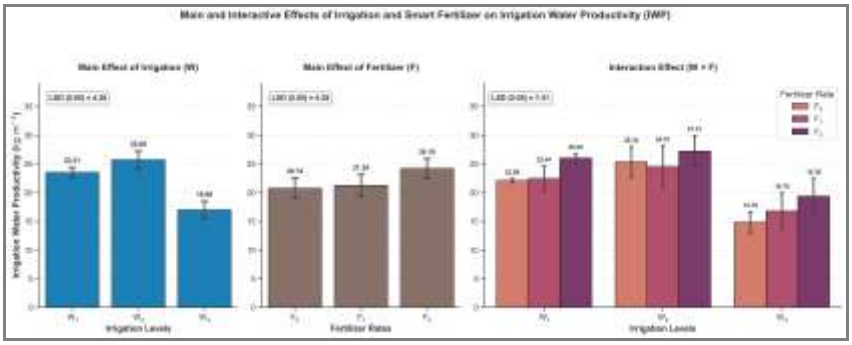


Figure 3: Main and interactive effects of soil moisture depletion thresholds (W) and smart foliar fertilizer rates (F) on Irrigation Water Productivity (IWP, kg m-3). The error bars represent the standard error (SE) of the means, and text boxes indicate the Least Significant Difference (LSD) at $P \leq 0.05$.

Natural Resources for Human Health
eISSN: 2583-1194

From the perspective of soil physics and fluid mechanics in porous media, this behavior is mechanistically explained by the laws of moisture transport. In the W_1 treatment, frequent irrigation intervals maintain the volumetric water content (θ) near field capacity (θ_{FC}). Hydraulically, this substantially increases the unsaturated hydraulic conductivity ($K(\theta)$) and the downward hydraulic gradient, thereby exacerbating non-productive hydrological losses via deep percolation (D) beyond the effective root zone depth (Z_r) (Zotarelli *et al.*, 2009). Conversely, the moderate depletion level (W_2) successfully balanced the soil water characteristic curve by constraining the gross applied irrigation (I_w) to precisely match the storage capacity of the active root zone, preventing deep percolation and maximizing the economic yield per applied drop (Playán & Mateos, 2006).

Under severe depletion conditions (W_3, 75%), the IWP collapsed to its lowest mean (16.98 kg m-3). The number of irrigation events was cut down but the very large amount irrigated to bring the water budget back into positive balance resulted in transient saturation followed by high stress and dominated the numerator. (economic yield, Y) in the efficiency equation.

Furthermore, the strategic interaction (W_2F_2) proved its efficacy by achieving the absolute maximum IWP (27.21 kg m-3) (Figure 3). This bio-hydrological superiority is attributed to the targeted foliar nutrient supply (F_2), which were not affected by the physical restrictions on the movement of nutrients in the inadequate soil solution. The exogenous nutrition allowed the crop to maintain photosynthetic efficiency and osmoregulation, and to maximize the economic output with the minimum gross hydrological inputs (Howell, 2001).

3.3. Partial Factor Productivity of Fertilizer (PFP): Agronomic Efficiency and Diminishing Returns

The agronomic and physiological behavior of the response of the Partial Factor Productivity of fertilizer (PFP) was complex, depending on the plant's ability to absorb the fertilizer and the energy status of the soil moisture in the porous media (Figure 4). The main effect analysis of fertilization showed a sharp drop in the efficiency of use of the higher fertilizer dose, while the half dose treatment (F_1) recorded a superior mean of 4791.67 $\mathrm{kg\ kg^{-1}}$, whereas the efficiency dropped drastically under the full-dose (F_2) to 2732.64 $\mathrm{kg\ kg^{-1}}$. This variance mathematically epitomizes the "Law of Diminishing Marginal Returns". Physiologically, this is said to be due to the stomatal absorption capacity and the rate of mesophyll assimilation becoming saturated. The maximum absolute yield is obtained with the full nutrient dose, however, nutrient efficiency is reduced; the high nutrient dose is thought to be beyond the plant's physiological ability to convert the added nutrients under the imposed environmental conditions and demonstrates why nutrient efficiency, not just absolute yield, must be considered. (Dobermann, 2007).

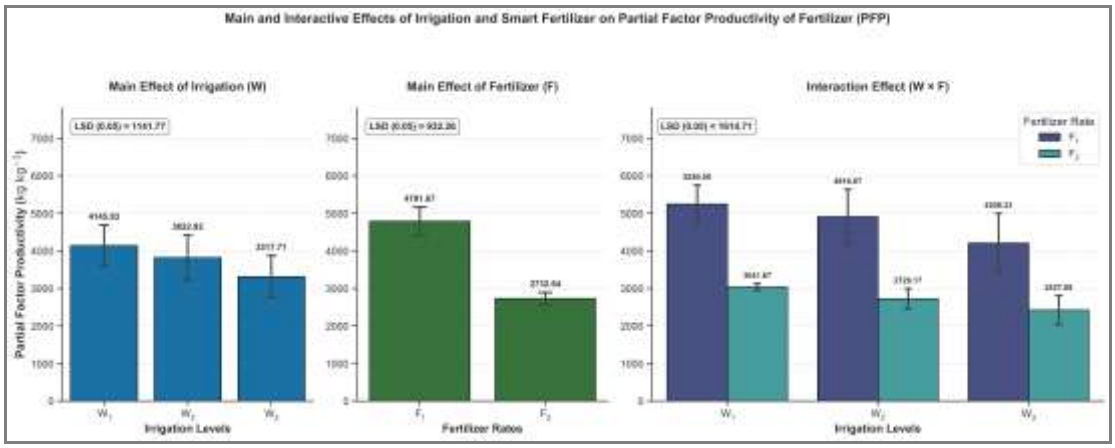


Figure 4: Main and interactive effects of soil moisture depletion thresholds (W) and smart foliar fertilizer rates (F) on the Partial Factor Productivity of Fertilizer (PFP, $\mathrm{kg\ kg^{-1}}$). The error bars represent the standard error (SE) of the means, and text boxes indicate the Least Significant Difference (LSD) at $P \leq 0.05$.

Hydraulically, the exacerbation of soil moisture depletion from 35% (W_1) to 75% (W_3) progressively stifled the fertilizer's efficiency (Figure 4). From a physical standpoint, even though the fertilizer was applied foliarly—bypassing the physical transport limitations within the soil solution—photosynthesis and dry matter accumulation fundamentally depend on the transpiration stream and cellular turgor pressure (ψ_p). The sharp decline in soil matric potential (ψ_m) under severe depletion conditions (W_3) reduces overall stomatal conductance, which consequently restricts the physiological ceiling of crop growth (Shock & Wang, 2011). As a result, the plant's capacity to utilize the applied foliar nutrients and convert them into economic yield is significantly diminished.

The interaction analysis ($W \times F$) clearly corroborated this hydro-physiological dynamic. The absolute highest fertilizer productivity (5250.00 $\mathrm{kg\ kg^{-1}}$) was recorded under the W_1F_1 interaction (Figure 4). Under this treatment, optimal moisture availability provided an active hydraulic architecture that allowed maximum utilization of the moderate fertilizer dose. Conversely, the W_3F_2 interaction recorded the lowest utilization efficiency (2427.08 $\mathrm{kg\ kg^{-1}}$). This mechanistically proves that attempting heavy nutritional compensation (F_2) under severe matric stress that inhibits cell elongation (W_3) constitutes a profound "physiological and economic waste" from an input efficiency perspective.

3.4. Variable Benefit-Cost Ratio (BCR): Lean Agricultural Economics and Bio-economic Resilience

Finally, for semi-arid water resource management, the Benefit-Cost Ratio (BCR), which is a ratio of physical and physiologic efficiencies, is the last step taken to quantify these efficiencies in monetary terms and is the essence of "Lean Thinking. When the main effects of irrigation were analysed (Figure 5), it was found that the moderate soil moisture depletion level (W_2, 40%) achieved the highest economic viability with a mean BCR of 14.24, visibly outperforming the well-irrigated regime (W_1) which recorded 13.07.

Mechanically speaking, this superiority is attributed from the point of agricultural hydrology and economics, by the fact that maintaining at 40% a depletion is sufficient to constrain the gross applied irrigation volume. (I_{gross}). This reduction lowers the variable costs associated with water pumping and supply (the denominator in the BCR equation), while simultaneously maintaining the soil matric potential (ψ_m) within an optimal range that prevents the degradation of the economic yield (the numerator) (Kijne *et al.*, 2003). In essence, the W_2 treatment eliminated the "hydraulic waste" (e.g., deep percolation) inherently associated with the frequent irrigations of W_1. Conversely, severe depletion (W_3, 75%) caused the economic indicator to plummet (9.45), because the physiological collapse and severe loss in biomass far outweighed the financial savings generated by reduced water inputs.

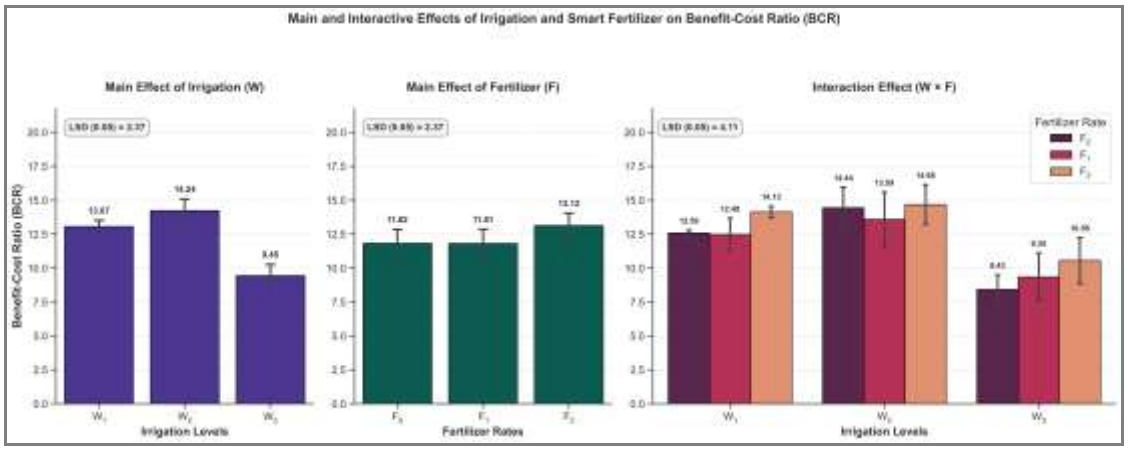


Figure 5: Main and interactive effects of soil moisture depletion thresholds (W) and smart foliar fertilizer rates (F) on the variable Benefit-Cost Ratio (BCR). The error bars represent the standard error (SE) of the means, and text boxes indicate the Least Significant Difference (LSD) at $P \leq 0.05$.

Regarding fertilization, the full-dose smart fertilizer (F_2) achieved the highest return on investment (13.12) compared to the control (F_0) (11.82). This indicates that the cost savings in economic yield due to the high efficiency of stomatal absorption, far outweighed the marginal cost of obtaining and applying the foliar fertilizer.

The strategic interaction (W_2F_2) culminated this bio-economic system by recording the absolute highest economic ratio (14.68) (Figure 5). Physically and economically, this interaction demonstrates that "Lean Management" does not necessarily imply the blind reduction of inputs, but rather their "engineering and biological optimization". While regulated deficit irrigation (W_2) eradicated water waste and curtailed its costs, the smart foliar fertilizer (F_2) physically bypassed the limitations of ionic transport in the soil, maximizing the final financial return at the lowest possible variable cost. This gives a comprehensive model on how to sustain agriculture in fragil environments. (Gittinger, 1982).

4. CONCLUSIONS AND RECOMMENDATIONS

This study shows that, based on the bio-physical/economic assessment of onion under different soil moisture energy and foliar nutrition, it could be concluded that the onion crop is best suited for moderate regulated deficit irrigation (RDI) threshold of 40% depletion (W_2) represents the optimal engineering and hydrological limit. This specific threshold dynamically balances the soil water characteristic curve, thereby eliminating the non-productive hydraulic waste, such as deep percolation, that is inherently associated with well-irrigated regimes (W_1). Consequently, this precise water management maximizes the Irrigation Water Productivity (IWP) to a peak of 25.69 $\mathrm{kg\ m^{-3}}$. Furthermore, smart foliar fertilization acts as a critical physiological buffer under severe soil matric stress (W_3). This supply of nutrients is exogenous, avoiding the nutrient paralysis and immobilization of the rhizosphere due to drought. (ψ_p) and stomatal conductance, ultimately rescuing structural vegetative growth from physiological collapse.

In terms of agronomic efficiency, the Partial Factor Productivity (PFP) model was strictly followed, and the Law of Diminishing Marginal Returns was observed. The full dose of fertilizer is recommended for autumn and spring growth. (F_2) maximized absolute biomass, the half-dose (F_1) exhibited a vastly superior nutrient utilization efficiency (4791.67 $\mathrm{kg\ kg^{-1}}$) per unit of applied mass, particularly under optimal moisture conditions. Ultimately, the strategic coupling of moderate moisture depletion with full-dose smart fertilization (W_2F_2) epitomizes the concept of lean agricultural management. By mathematically minimizing gross hydrological inputs and variable costs, while biologically maximizing the economic yield, this bio-economic interaction was the highest absolute BCR at 14.68.

Moving forward, it is highly recommended to adopt this bio-economic synergy for shallow-rooted crops in semi-arid regions and to shift towards targeted smart foliar applications during anticipated drought spells to circumvent matric potential (ψ_m) constraints. The use of real-time soil moisture sensors like time-domain reflectometry (TDR) or tensiometers should be incorporated into future hydrological frameworks to continually monitor matric potential and to maintain the matric potential to 40% depletion with high precision at the field scale.

REFERENCES

[1] Ali, M. H., & Talukder, M. S. U. (2008). Increasing water productivity in crop production—A synthesis. *Agricultural Water Management*, *95*(11), 1201–1213. https://doi.org/10.1016/j.agwat.2008.06.008

[2] Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements* (FAO Irrigation and Drainage Paper No. 56). Food and Agriculture Organization of the United Nations. https://www.fao.org/4/x0490e/x0490e00.htm

[3] Bekele, S., & Tilahun, K. (2007). Regulated deficit irrigation scheduling of onion in a semiarid region of Ethiopia. *Agricultural Water Management*, *89*(1–2), 148–152. https://doi.org/10.1016/j.agwat.2007.01.002

[4] Camp, C.R. (1998). Subsurface Drip Irrigation: A Review. *Transactions of the ASAE*, 41, 1353-1367. https://www.ars.usda.gov/ARSUserFiles/60820000/Manuscripts/1998/Man478.pdf

[5] Cao, Y., Turk, K., Bibi, N., Ghafoor, A., Ahmed, N., Azmat, M., Ahmed, R., Ghani, M. I., & Ahanger, M. A. (2025). Nanoparticles as catalysts of agricultural revolution: Enhancing crop tolerance to abiotic stress: A review. *Frontiers in Plant Science*, *15*, Article 1510482. https://doi.org/10.3389/fpls.2024.1510482

[6] Dane, J. H., & Topp, G. C. (Eds.). (2002). *Methods of soil analysis: Part 4. Physical methods* (Soil Science Society of America Book Series, No. 5). Soil Science Society of America. https://doi.org/10.2136/sssabookser5.4

[7] Dimkpa, C. O., Andrews, J., Sanabria, J., Bindraban, P. S., Singh, U., Elmer, W. H., Gardea-Torresdey, J. L., & White, J. C. (2020). Interactive effects of drought, organic fertilizer, and zinc oxide nanoscale and bulk particles on wheat performance and grain nutrient accumulation. *Science of The Total Environment*, *722*, Article 137808. https://doi.org/10.1016/j.scitotenv.2020.137808

[8] Dobermann, A. (2007). Nutrient Use Efficiency: Measurement and Management. IFA International Workshop on Fertilizer Best Management Practices, Brussels, 1-28. https://www.scirp.org/reference/referencespapers?referenceid=2396329

[9] FAO. (2021). *The state of the world's land and water resources for food and agriculture: Systems at breaking point. Synthesis report 2021*. FAO. https://doi.org/10.4060/cb7654en

[10] Fereres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, *58*(2), 147–159. https://doi.org/10.1093/jxb/erl165

[11] Fernández, V., & Brown, P. H. (2013). From plant surface to plant metabolism: The uncertain fate of foliar-applied nutrients. *Frontiers in Plant Science*, *4*, Article 289. https://doi.org/10.3389/fpls.2013.00289

[12] Gittinger, J. P. (1982). *Economic analysis of agricultural projects* (2nd ed.). Johns Hopkins University Press. https://books.google.iq/books/about/Economic_Analysis_of_Agricultural_Projec.html?id=CJmRAAAAIAAJ&redir_esc=y

[13] Hillel, D. (1998). *Environmental soil physics: Fundamentals, applications, and environmental considerations*. Academic Press. https://www.educate.elsevier.com/book/details/9780123485250

[14] Howell, T. A. (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, *93*(2), 281-289. https://doi.org/10.2134/agronj2001.932281x

[15] Kijne, J. W., Barker, R., & Molden, D. (Eds.). (2003). *Water productivity in agriculture: Limits and opportunities for improvement* (Comprehensive Assessment of Water Management in Agriculture Series 1). CABI; International Water Management Institute (IWMI). https://doi.org/10.1079/9780851996691.0000

[16] López-Vargas, E. R., Hidalgo-Martínez, D., Camacho-Nieto, O., Zepeda-Vallejo, L. G., Pérez-Álvarez, M., Cadenas-Pliego, G., Hernández-Fuentes, A. D., & Becerra-Martínez, E. (2026). Reprogramming of black bean leaf metabolism by zinc nanofertilizers and biofertilizers revealed through NMR metabolomics. *Environmental Science: Nano*, *13*(5), 2396–2411. https://doi.org/10.1039/d5en00872g

[17] Marschner, P. (Ed.). (2012). *Marschner's mineral nutrition of higher plants* (3rd ed.). Academic Press. https://doi.org/10.1016/C2009-0-63043-9

[18] Meier, U. (2001). Growth stages of mono-and dicotyledonous plants, BBCH Monograph. *Federal Biological Research Centre for Agriculture and Forestry*. https://plantevaernonline.dlbr.dk/cp/Documents/bbcheng.pdf

[19] Playán, E., & Mateos, L. (2006). Modernization and optimization of irrigation systems to increase water productivity. *Agricultural Water Management*, *80*(1–3), 100–116. https://doi.org/10.1016/j.agwat.2005.07.007

[20] Pokhrel, Y., Felfelani, F., Satoh, Y., Boulange, J., Burek, P., Hanasaki, N., Huang, J., Schmied, H. M., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Aristeidis, K., Clark, M., Cummings, C., Döll, P., Livneh, B., Prudhomme, C., ... Kim, H. (2021). Global terrestrial water storage and drought severity under climate change. *Nature Climate Change*, *11*(3), 226–233. https://doi.org/10.1038/s41558-020-00972-w

[21] Rosa, L., Rulli, M. C., Davis, K. F., Chiarelli, D. D., Passera, C., & D'Odorico, P. (2020). Global agricultural economic water scarcity. *Science Advances*, *6*(18), Article eaaz6031. https://doi.org/10.1126/sciadv.aaz6031

[22] Shock, C. C., & Wang, F. (2011). Soil water tension, a powerful measurement for productivity and stewardship. *HortScience*, *46*(2), 178–185. https://doi.org/10.21273/HORTSCI.46.2.178

[23] Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., Johnston, C. T., & Sumner, M. E. (Eds.). (1996). *Methods of soil analysis: Part 3. Chemical methods* (Soil Science Society of America Book Series, No. 5). Soil Science Society of America. https://doi.org/10.2136/sssabookser5.3.index

[24] Wakchaure, G. C., Minhas, P. S., Meena, K. K., Singh, N. P., Hegade, P. M., & Sorty, A. M. (2018). Growth, bulb yield, water productivity and quality of onion (*Allium cepa* L.) as affected by deficit irrigation regimes and exogenous application of plant bio–regulators. *Agricultural Water Management*, *199*, 1–10. https://doi.org/10.1016/j.agwat.2017.11.026

[25] Wang, M., Zheng, Q., Shen, Q., & Guo, S. (2013). The critical role of potassium in plant stress response. *International Journal of Molecular Sciences*, *14*(4), 7370–7390. https://doi.org/10.3390/ijms14047370

[26] Weaver, J. E. (1926). *Root development of field crops*. McGraw-Hill Book Company. https://openlibrary.org/books/OL6689089M/Root_development_of_field_crops

[27] Wei, J., Liu, L., Wei, Z., Qin, Q., Bai, Q., Zhao, C., Zhang, S., & Wang, H. (2025). Silicon nano-fertilizer-enhanced soybean resilience and yield under drought stress. *Plants*, *14*(5), Article 751. https://doi.org/10.3390/plants14050751

[28] Zahedi, S. M., Hosseini, M. S., Daneshvar Hakimi Meybodi, N., & Teixeira da Silva, J. A. (2019). Foliar application of selenium and nano-selenium affects pomegranate (*Punica granatum* cv. Malase Saveh) fruit yield and quality. *South African Journal of Botany*, *124*, 352–358. https://doi.org/10.1016/j.sajb.2019.05.019

[29] Zotarelli, L., Dukes, M. D., Scholberg, J. M. S., Muñoz-Carpena, R., & Icerman, J. (2009). Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. *Agricultural Water Management*, *96*(8), 1247–1258. https://doi.org/10.1016/j.agwat.2009.03.019