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Efficiency of Using Plant Residues, Bio fertilizers and Irrigation Intervals in the Growth and Yield of Beet Plants to Achieve Sustainable Agriculture

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ABSTRACT

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The experiment was conducted an extension center in the Holy Karbal Governorate during the 2024-2025 growing season, the aim was to study the efficiency of using plant residues, bio fertilizers, and irrigation intervals in the growth and yield of sugar beet plants to achieve sustainable agriculture. The field was divided into three replicates, each consisting of 27 experimental units, in each experimental unit, 20 plants of the Detroit variety were sown using drip irrigation systems. Sowing took place from October 15, 2024, to February 15, 2025. Three factors were used: The first factor consisted of three irrigation intervals levels, it is symbolized A1 (irrigation according to field capacity), A2 (irrigation three day after field capacity) and A3 (irrigation six days after field capacity), the second factor consisted of three levels of fertilization with plant residues, it is symbolized B1 (the control treatment, adding NPK + Urea chemical fertilizer), B2: Adding palm frond residues with 25% NPK + Urea and B3: Adding rice residues with 25% NPK + Urea, the third factor consisted of three levels of bio fertilization it is symbolized C1: Control treatment without addition, C2: Adding Trichoderma fungus and C3: Adding Mycorrhizal fungus. The results showed that adding palm frond and rice residues and adding Trichoderma and Mycorrhizal fungi had a positive effect on all studied traits, no significant differences were observed when irrigation was delayed beyond the plant and soil's field capacity requirements, also when compared to chemical fertilization with NPK and Urea, this contributes to reducing the use of chemical fertilizers, mitigating environmental pollution and optimizing the use of natural resources and achieving sustainable agriculture.

1-Introduction

The pursuit of sustainable agriculture represents a paramount challenge for the 21st century, necessitating a fundamental shift from input-intensive practices towards ecological resource management. This paradigm aims to reconcile the urgent need for global food security with the imperative of preserving ecosystem integrity, enhancing soil health, and mitigating environmental degradation. Within this context, the cultivation of beet (*Beta vulgaris* L.), a crop of significant nutritional and economic value rich in antioxidants, betalains, and essential minerals, presents a critical opportunity to implement and evaluate sustainable agronomic strategies.

Conventional beet production systems often rely heavily on synthetic fertilizers and unrestrictive irrigation; practices associated with considerable drawbacks. These include the degradation of soil structure, depletion of organic matter, contamination of water bodies through nutrient leaching, increased greenhouse gas emissions, and the unsustainable consumption of freshwater resources. Consequently, there is a pressing need to develop and integrate alternative, nature-based solutions that can maintain or enhance crop productivity while fostering agricultural sustainability.

Three promising, interrelated approaches have emerged at the forefront of this agroecological transition: the incorporation of plant residues, the application of biofertilizers, and the strategic management of irrigation. First, the utilization of plant residues (e.g., from preceding cereal or legume crops) as soil amendments offers a direct pathway to recycle organic matter and nutrients [1]. Their decomposition enhances soil physicochemical and biological properties, improving water retention, cation exchange capacity, and long-term fertility, while potentially suppressing soil-borne pathogens. Second, biofertilizers—consortia of beneficial microorganisms such as nitrogen-fixing bacteria

(e.g., *Azotobacter*, *Rhizobium*), phosphate-solubilizing bacteria (e.g., *Pseudomonas*, *Bacillus*), and arbuscular mycorrhizal fungi—act as catalysts for nutrient cycling [2]. By facilitating the mobilization of naturally occurring but often inaccessible soil nutrients, these microorganisms reduce dependency on synthetic inputs and promote plant growth through direct and indirect mechanisms, including phytohormone production and induced systemic resistance [3].

Third, optimizing irrigation intervals is critical for enhancing water-use efficiency (WUE), a non-negotiable aspect of sustainability in an era of increasing water scarcity [4]. Deficit irrigation or regulated irrigation scheduling strategies can encourage deeper root development, moderate plant vegetative growth, and potentially improve the partitioning of photo assimilates to the economically valuable root organ, without incurring significant yield penalties [5]. However, the efficacy of water conservation strategies is profoundly influenced by soil conditions, which are themselves modulated by organic amendments and microbial activity [6].

While the individual benefits of these practices have been documented in various cropping systems, a significant knowledge gap persists regarding their integrated and synergistic effects on beet cultivation [7]. It remains inadequately explored how the improved soil moisture dynamics from residue incorporation interact with tailored irrigation schedules, and how these conditions, in turn, influence the establishment and efficacy of introduced biofertilizer consortia. A systems-based investigation is therefore essential to determine optimal combinations that maximize resource efficiency, yield, and crop quality [8].

Therefore, the study is unique in using the three combinations (irrigation intervals, organic fertilization, bio fertilization) to evaluate the efficiency of plant residues (palm fronds and rice residues) and bio fertilizers (*Trichoderma* and *Mycorrhizae*) and their effect on plant

resistance to environmental and biological stresses and improving growth and yield, and the optimal use of water resources, which is in line with the requirements of sustainable agricultural development.

2-Materials and Methods

2.1. Site Description

The field experiment was conducted during the 2024-2025 growing season at the desert demonstration farm affiliated with the Ministry of Agriculture, located in the Holy City of Karbala, Iraq. The objective was to evaluate the interactive effects of plant residues, bio-fertilizers, and irrigation intervals on the growth and yield of sugar beet (*Beta vulgaris* L.) within a framework of sustainable agricultural practices. The soil at the experimental site is classified as sandy loam, with physical and chemical properties detailed in Table 1.

Table (1): Physical and Chemical Properties of the Field Soil.

| Soil Texture | | | Bulk density | N ppm | P ppm | K ppm | Organic Matter % | Electrical Conductivity dc.cm | PH |
|--------------|------|------|--------------|-------|-------|-------|------------------|-------------------------------|------|
| Silt | Clay | Sand | | | | | | | |
| 27.5 | 11.5 | 61 | 1.18 | 37 | 6.74 | 154 | 0.83 | 4.2 | 7.18 |

2.2. Experimental Design The experiment was established as a **factorial split-split-plot design** arranged in a **Randomized Complete Block Design (RCBD)** with three replications. The treatments were distributed as follows:

- **Main Plots:** Irrigation intervals (Factor A).
- **Sub-plots:** Plant residue amendments (Factor B).
- **Sub-sub-plots:** Bio-fertilizer applications (Factor C).

This resulted in 27 treatment combinations ($3 \times 3 \times 3$). Each experimental unit measured 1 m², containing four rows with an inter-row spacing of 25 cm and an intra-row plant spacing of 20 cm, totaling 20 plants per unit. A 1 m buffer separated experimental units within a replication, and a 2 m alley separated the three replications, culminating in a total of 81 experimental units.

2.3. Treatment Details

Three experimental factors were investigated, each comprising three levels.

- **Factor A: Irrigation Intervals**
 - **A1:** Control (Irrigation at field capacity based on plant and soil requirement).
 - **A2:** Irrigation applied 3 days after reaching field capacity.
 - **A3:** Irrigation applied 6 days after reaching field capacity.
 - Field capacity (FC) was determined gravimetrically [10]. Irrigation treatments commenced three weeks after germination, coinciding with the establishment of true leaves and the onset of autotrophic growth. A depletion level of 50% of available water was maintained for the sugar beet crop.
- **Factor B: Plant Residue Amendments**
 - **B1:** Control (100% recommended dose of chemical NPK and Urea fertilizer).
 - **B2:** Partially decomposed palm frond residues (40 tons ha⁻¹) + 25% of the recommended NPK and Urea dose.
 - **B3:** Partially decomposed rice straw residues (40 tons ha⁻¹) + 25% of the recommended NPK and Urea dose.
 - The chemical properties of the applied plant residues are presented in Table 2.

Table (2): Chemical and Physical Properties of the plant Residues

| | EC dc.cm | pH | C % | C/N % | N % | P % | K % |
|---------------------|----------|------|-------|-------|------|------|------|
| Palm frond Residues | 2.66 | 7.04 | 43.70 | 19.00 | 2.30 | 0.65 | 2.8 |
| Rice Residues | 0.93 | 6.50 | 44.6 | 18.0 | 2.48 | 0.54 | 0.26 |

• Factor C: Bio-fertilizer Inoculation

- **C1:** Control (no bio-fertilizer).
- **C2:** *Trichoderma* spp. (Isolate T6) at an inoculant density of 7×10^{11} CFU mL⁻¹. Application: 10 g per planting hole during sowing [10].
- **C3:** Mycorrhizal fungi (*Glomus* spp.) at an inoculant density of 50 spores per gram of soil. Application: 10 g per planting hole during sowing [11].

All collected data were subjected to analysis of variance (ANOVA) appropriate for a split-split-plot design using SAS (version 9.4) or an equivalent statistical software. Treatment means were compared using the **Least Significant Difference (LSD)** test at a significance level of $p \leq 0.05$.

2.4. Measurements

Data were collected on growth parameters (e.g., plant height, leaf area index), yield components (e.g., root diameter, fresh and dry root weight), and quality traits (e.g., sucrose content). Measurements were taken from ten randomly selected, competitively positioned plants within the central rows of each experimental unit at designated phenological stages.

3-Results

3.1. Leaf Macronutrient Content

The concentrations of nitrogen (N), phosphorus (P), and potassium (K) in sugar beet leaves were significantly affected by irrigation intervals, plant residues, and bio-fertilizers, both individually and in their interactions.

2.5. Statistical Analysis

Table 3: Effect of irrigation intervals, plant residues, and bio fertilization on the percentage of nitrogen in beetroot leaves.

| Percentage of nitrogen in leaves (%) | | | | | | |
|--------------------------------------|---------------------|----------------------|-------|-------|------------------|-----------------|
| Irrigation Intervals A | Plant Residues B | Bio fertilizers C | | | A*B | A |
| | | C1 | C2 | C3 | | |
| A1 | B1 | 4.010 | 4.230 | 4.150 | 4.130 | 3.938 |
| | B2 | 3.750 | 3.960 | 3.830 | 3.847 | |
| | B3 | 3.820 | 3.880 | 3.810 | 3.837 | |
| A2 | B1 | 3.560 | 3.780 | 3.700 | 3.680 | 3.626 |
| | B2 | 3.400 | 3.710 | 3.680 | 3.597 | |
| | B3 | 3.470 | 3.670 | 3.660 | 3.600 | |
| A3 | B1 | 1.830 | 2.020 | 2.030 | 1.960 | 1.983 |
| | B2 | 1.870 | 2.010 | 2.050 | 1.977 | |
| | B3 | 1.890 | 2.070 | 2.080 | 2.013 | |
| LSD=0.05 | | LSD ABC 0.3675 | | | LSD AB 0.1479 | LSD A 0.1112 |
| A*C | | | | | | |
| A1 | | 3.860 | 4.023 | 3.930 | | |
| A2 | | 3.477 | 3.720 | 3.680 | | |
| A3 | | 1.863 | 2.033 | 2.053 | | LSD AC 0.2131 |

| | | B* C | | B |
|----------|-------|---------------|-------|--------------|
| B1 | 3.133 | 3.343 | 3.293 | 3.257 |
| B2 | 3.007 | 3.227 | 3.187 | 3.140 |
| B3 | 3.060 | 3.207 | 3.183 | 3.150 |
| LSD=0.05 | | LSD BC 0.2123 | | LSD B 0.0876 |
| C | 3.067 | 3.259 | 3.221 | LSD C 0.1398 |

*A1: Irrigation at field capacity. A2: Irrigation 3 days after FC. A3: Irrigation 6 days after FC. B1: 100% NPK+Urea. B2: Palm residue (40 t ha⁻¹) + 25% NPK. B3: Rice residue (40 t ha⁻¹) + 25% NPK.

C1: Control (no bio-fertilizer). C2: Trichoderma. C3: Mycorrhizae.

* Means within the same category (column or row) followed by different letters are significantly different at $p \leq 0.05$.

The main effect of irrigation was highly significant. The optimal irrigation treatment (A1) resulted in the highest leaf N content (3.94%), which was significantly greater than that under moderate (A2, 3.63%) and severe (A3, 1.98%) deficit irrigation. Among plant residue treatments, the full chemical fertilizer application (B1) yielded the highest leaf N (3.26%), significantly outperforming the combined residue treatments (B2 and B3). Bio-fertilization significantly enhanced leaf N, with *Trichoderma* (C2) recording the highest value (3.26%).

Significant interactions were observed. The two-way interaction A×B showed the highest leaf N in treatment A1B1 (4.13%), while the lowest was in A3B1 (1.96%). The three-way interaction (A×B×C) revealed that the highest leaf N content was achieved in treatment A1B1C2 (4.23%). Notably, several

combinations under deficit irrigation, such as A2B2C2 (3.71%), were statistically comparable to the optimal control treatment A1B1C1 (4.01%).

Table 4 & 5 (presented in a similar, concise format) showed analogous trends for leaf P and K. Deficit irrigation (A3) significantly reduced both P and K concentrations. For P, the main effect of bio-fertilizer C3 (Mycorrhizae) was most effective (0.427%). For K, bio-fertilizer C2 (*Trichoderma*) yielded the highest value (3.78%). The interaction effects indicated that integrated applications, such as A1B1C3 for P and A1B1C2 for K, achieved peak values. Importantly, combinations like A2B1C3 for P and A2B2C3 for K showed no significant difference from the fully irrigated, chemically fertilized control (A1B1C1).

Table 4: Effect of irrigation intervals, plant

residues, and bio fertilization on the percentage of Phosphorus in beetroot leaves.

| Percentage of Phosphorus in leaves (%) | | | | | | |
|--|---------------------|----------------------|--------|--------|----------------|---------------|
| Irrigation Intervals A | Plant Residues B | Bio fertilizers C | | | A*B | A |
| | | C1 | C2 | C3 | | |
| A1 | B1 | 0.4690 | 0.5040 | 0.5420 | 0.5050 | 0.4726 |
| | B2 | 0.4130 | 0.4470 | 0.4850 | 0.4483 | |
| | B3 | 0.4310 | 0.4650 | 0.4970 | 0.4643 | |
| A2 | B1 | 0.4360 | 0.4620 | 0.5090 | 0.4690 | 0.4238 |
| | B2 | 0.3810 | 0.3740 | 0.4520 | 0.4023 | |
| | B3 | 0.3880 | 0.3980 | 0.4140 | 0.4000 | |
| A3 | B1 | 0.3050 | 0.2310 | 0.2580 | 0.2647 | 0.2993 |
| | B2 | 0.2690 | 0.3030 | 0.3310 | 0.3010 | |
| | B3 | 0.2970 | 0.3410 | 0.3590 | 0.3323 | |
| LSD=0.05 | | LSD ABC 0.11373 | | | LSD AB 0.05239 | LSD A 0.02519 |
| A*C | | | | | | |
| A1 | | 0.4377 | 0.4720 | 0.5080 | LSD AC 0.06223 | |

| | | | | |
|----------|--------|----------------|--------|---------------|
| A2 | 0.4017 | 0.4113 | 0.4583 | |
| A3 | 0.2903 | 0.2917 | 0.3160 | |
| B* C | | | | |
| B1 | 0.4033 | 0.3990 | 0.4363 | 0.4129 |
| B2 | 0.3543 | 0.3747 | 0.4227 | 0.3839 |
| B3 | 0.3720 | 0.4013 | 0.4233 | 0.3989 |
| LSD=0.05 | | LSD BC 0.06749 | | LSD B 0.03519 |
| C | 0.3766 | 0.3917 | 0.4274 | LSD C 0.04219 |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). * C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

Table 5: Effect of irrigation intervals, plant residues, and bio fertilization on the percentage of potassium in beetroot leaves.

| Percentage of potassium in leaves (%) | | | | | | |
|---------------------------------------|----------------|-----------------|-------|---------------|--------------|--------|
| Irrigation Intervals | Plant Residues | Bio fertilizers | | | A*B | A |
| | | C | | | | |
| A | B | C1 | C2 | C3 | | |
| A1 | B1 | 4.340 | 4.680 | 4.560 | 4.527 | 4.300 |
| | B2 | 4.080 | 4.250 | 4.290 | 4.207 | |
| | B3 | 3.990 | 4.300 | 4.210 | 4.167 | |
| A2 | B1 | 3.860 | 4.050 | 4.080 | 3.997 | 3.891 |
| | B2 | 3.790 | 3.870 | 3.910 | 3.857 | |
| | B3 | 3.710 | 3.920 | 3.830 | 3.820 | |
| A3 | B1 | 2.520 | 3.060 | 2.840 | 2.807 | 2.894 |
| | B2 | 2.860 | 2.930 | 2.970 | 2.920 | |
| | B3 | 2.800 | 2.980 | 3.090 | 2.957 | |
| LSD=0.05 | | LSD ABC 0.8185 | | LSD AB 0.4659 | LSD A 0.3683 | |
| A*C | | | | | | |
| A1 | | 4.137 | 4.410 | 4.353 | | |
| A2 | | 3.787 | 3.947 | 3.940 | | |
| A3 | | 2.727 | 2.990 | 2.967 | LSD AC | 0.4903 |
| B* C | | | | | | |
| B1 | | 3.573 | 3.930 | 3.827 | | 3.777 |
| B2 | | 3.577 | 3.683 | 3.723 | | 3.661 |
| B3 | | 3.500 | 3.733 | 3.710 | | 3.648 |
| LSD=0.05 | | LSD BC 0.4697 | | LSD B 0.2673 | | |
| C | | 3.550 | 3.782 | 3.753 | LSD C | 0.2850 |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). * C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

3.2. Growth Parameters and Yield

Growth parameters were significantly constrained by water deficit. Leaf area (Table 6), shoot dry weight (Table 7), and total root yield (Table 8) were maximized under optimal irrigation (A1). For instance, A1 produced a leaf area of 158.6 dm², a shoot dry weight of 25.38 g, and a root yield of 63.21 t ha⁻¹, all significantly higher than under severe deficit (A3). The main effect of plant residues showed that chemical fertilization (B1) often yielded

the highest values for growth and yield. The application of bio-fertilizers (C2, C3) consistently improved these parameters compared to the control (C1).

Significant interaction effects demonstrated the potential of integrated management. For leaf area, the combination A1B1C3 gave the highest value (166.25 dm²). Under moderate water deficit (A2), treatment A2B3C3 (153.35 dm²) was statistically equivalent to A1B1C1 (160.58 dm²). For total root yield, the highest value was

in A1B1C2 (65.71 t ha⁻¹). However, the yield from A2B3C2 (59.94 t ha⁻¹) under water stress

was not significantly different from that of A1B1C1 (64.07 t ha⁻¹).

Table 6: Effect of irrigation intervals, plant residues, and bio fertilization on the Leaf area of the beetroot.

| Irrigation Intervals A | Plant Residues B | Bio fertilizers C | | | A*B | A | |
|---------------------------|---------------------|----------------------|--------|--------|--------|-------------|----------------|
| | | C1 | C2 | C3 | | | |
| | | LSD=0.05 | | | | | LSD ABC 10.296 |
| A1 | B1 | 160.58 | 163.34 | 166.25 | 163.39 | 158.59 | |
| | B2 | 151.37 | 155.76 | 157.07 | 154.73 | | |
| | B3 | 154.48 | 157.49 | 160.94 | 157.64 | | |
| A2 | B1 | 146.99 | 150.75 | 149.66 | 149.13 | 147.00 | |
| | B2 | 137.78 | 147.17 | 146.48 | 143.81 | | |
| | B3 | 140.89 | 149.90 | 153.35 | 148.05 | | |
| A3 | B1 | 112.84 | 126.60 | 120.51 | 119.98 | 125.07 | |
| | B2 | 115.63 | 130.02 | 126.33 | 123.99 | | |
| | B3 | 123.74 | 136.75 | 133.20 | 131.23 | | |
| | | A*C | | | | | |
| | A1 | 155.48 | 158.86 | 161.42 | | | |
| | A2 | 141.89 | 149.27 | 149.83 | | | |
| | A3 | 117.40 | 131.12 | 126.68 | LSD AC | 6.369 | |
| | | B* C | | | | B | |
| | B1 | 140.14 | 146.90 | 145.47 | | 144.17 | |
| | B2 | 134.93 | 144.32 | 143.29 | | 140.85 | |
| | B3 | 139.70 | 148.05 | 149.16 | | 145.64 | |
| | | LSD=0.05 | | | LSD BC | 5.842 | LSD B 3.531 |
| | C | 138.26 | 146.42 | 145.98 | | LSD C 3.456 | |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). *C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

Table 7: Effect of irrigation intervals, plant residues, and bio fertilization on the Dry weight of shoot of the beetroot.

| Irrigation Intervals A | Plant Residues B | Bio fertilizers C | | | A*B | A |
|---------------------------|---------------------|----------------------|-------|-------|-------|-------|
| | | C1 | C2 | C3 | | |
| | | LSD=0.05 | | | | |
| A1 | B1 | 26.27 | 28.99 | 28.01 | 27.76 | 25.38 |
| | B2 | 22.35 | 26.05 | 25.23 | 24.54 | |
| | B3 | 23.07 | 24.19 | 24.29 | 23.85 | |
| A2 | B1 | 20.80 | 25.52 | 24.54 | 23.62 | 22.58 |
| | B2 | 18.88 | 23.58 | 22.76 | 21.74 | |
| | B3 | 19.60 | 22.72 | 24.82 | 22.38 | |
| A3 | B1 | 15.45 | 20.17 | 19.19 | 18.27 | 17.12 |
| | B2 | 15.53 | 17.23 | 18.41 | 17.06 | |
| | B3 | 14.25 | 16.37 | 17.47 | 16.03 | |
| | | A*C | | | | |

| | | | | |
|----------|-------|--------------|-------|--------------|
| A1 | 23.90 | 26.41 | 25.84 | LSD AC 4.262 |
| A2 | 19.76 | 23.94 | 24.04 | |
| A3 | 15.08 | 17.92 | 18.36 | |
| | | B* C | | B |
| B1 | 20.84 | 24.89 | 23.91 | 23.22 |
| B2 | 18.92 | 22.29 | 22.13 | 21.11 |
| B3 | 18.97 | 21.09 | 22.19 | 20.75 |
| LSD=0.05 | | LSD BC 3.721 | | LSD B 2.201 |
| C | 19.58 | 22.76 | 22.75 | LSD C 2.223 |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). * C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

Table 8: Effect of irrigation intervals, plant residues, and bio fertilization on the Total yield of roots of the beetroot.

| Irrigation Intervals | Plant Residues | Bio fertilizers | | | A*B | A | |
|----------------------|----------------|-----------------|-------|--------------|--------------|-------|----|
| | | B | C | | | | |
| | | | C1 | C2 | | | C3 |
| A1 | B1 | 64.07 | 65.71 | 64.70 | 64.83 | 63.21 | |
| | B2 | 60.02 | 63.66 | 62.23 | 61.97 | | |
| | B3 | 61.63 | 64.04 | 62.83 | 62.84 | | |
| A2 | B1 | 56.17 | 58.61 | 58.19 | 57.66 | 57.75 | |
| | B2 | 54.51 | 58.96 | 58.53 | 57.33 | | |
| | B3 | 55.33 | 59.94 | 59.53 | 58.27 | | |
| A3 | B1 | 49.56 | 52.01 | 50.99 | 50.86 | 52.02 | |
| | B2 | 49.31 | 54.35 | 53.13 | 52.26 | | |
| | B3 | 49.73 | 54.54 | 54.52 | 52.93 | | |
| LSD=0.05 | | LSD ABC 12.677 | | LSD AB 6.529 | LSD A 4.565 | | |
| | | A*C | | | | | |
| A1 | | 61.91 | 64.47 | 63.25 | LSD AC 7.271 | | |
| A2 | | 55.34 | 59.17 | 58.75 | | | |
| A3 | | 49.53 | 53.63 | 52.88 | | | |
| | | B* C | | | | B | |
| B1 | | 56.60 | 58.78 | 57.96 | 57.78 | | |
| B2 | | 54.61 | 58.99 | 57.96 | 57.19 | | |
| B3 | | 55.56 | 59.51 | 58.96 | 58.01 | | |
| LSD=0.05 | | LSD BC 7.392 | | LSD B 4.009 | | | |
| C | | 55.59 | 59.09 | 58.30 | LSD C 4.564 | | |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). * C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

3.3. Root Quality Attributes

Root quality, assessed through betalain, total soluble solids (TSS), ascorbic acid, and folic acid, was significantly influenced. Betalain and Antioxidants: Optimal irrigation (A1) and chemical fertilization (B1) generally promoted the highest accumulation of betalain, ascorbic acid, and folic acid (Tables 9, 11, 12). Bio-fertilizers, particularly *Trichoderma* (C2), consistently enhanced these compounds. The three-way

interaction showed A1B1C2 had the maximum betalain (14.92 mg g⁻¹), yet A2B3C2 (12.10 mg g⁻¹) was comparable to A1B1C1 (12.45 mg g⁻¹). Total Soluble Solids (TSS): TSS was highest under A1 and with chemical fertilizer B1 (Table 10). Bio-fertilizer C2 recorded the highest value (10.96%). The interaction A1B1C2 yielded the maximum TSS (13.97%). Ascorbic Acid: Content was highest under A1 (14.84 mg/100g) and with B1 (13.98 mg/100g). Bio-fertilizer C3 was most

effective (13.65 mg/100g). The combination A1B1C3 achieved the peak value (17.97 mg/100g). Folic Acid: A1 and B1 treatments yielded the highest folic acid content. Bio-fertilizer C3 was superior (315.4 µg/100g). The three-way interaction showed A1B1C3 had the maximum (399.1 µg/100g), but A2B3C3 (333.2 µg/100g) was statistically similar to A1B1C1 (367.0 µg/100g). A

critical finding across all quality traits was that specific combinations of deficit irrigation (A2), plant residues, and bio-fertilizers produced results statistically equivalent to the optimal water and chemical fertilizer control (A1B1C1).

Table 9: Effect of irrigation intervals, plant residues, and bio fertilization on the betalain pigment in roots mg. g⁻¹ fresh weight of the beetroot.

| Estimation of betalain in roots mg. g ⁻¹ fresh weight | | | | | | |
|--|---------------------|----------------------|-------|-------|--------------|--------------|
| Irrigation Intervals A | Plant Residues B | Bio fertilizers C | | | A*B | A |
| | | C1 | C2 | C3 | | |
| A1 | B1 | 12.45 | 14.92 | 13.59 | 13.65 | 11.83 |
| | B2 | 9.35 | 11.50 | 10.45 | 10.43 | |
| | B3 | 10.34 | 12.43 | 11.41 | 11.39 | |
| A2 | B1 | 11.10 | 13.68 | 12.29 | 12.36 | 11.23 |
| | B2 | 9.09 | 10.96 | 10.12 | 10.06 | |
| | B3 | 10.22 | 12.10 | 11.48 | 11.27 | |
| A3 | B1 | 7.94 | 10.51 | 9.99 | 9.48 | 8.84 |
| | B2 | 5.99 | 9.20 | 8.15 | 7.78 | |
| | B3 | 6.52 | 10.17 | 11.12 | 9.27 | |
| LSD=0.05 | | LSD ABC 2.601 | | | LSD AB 1.106 | LSD A 0.746 |
| A*C | | | | | | |
| A1 | | 10.71 | 12.95 | 11.82 | | |
| A2 | | 10.14 | 12.25 | 11.30 | | LSD AC 1.484 |
| A3 | | 6.82 | 9.96 | 9.75 | | |
| B* C | | | | | | |
| | B1 | 10.50 | 13.04 | 11.96 | | 11.83 |
| | B2 | 8.14 | 10.55 | 9.57 | | 9.42 |
| | B3 | 9.03 | 11.57 | 11.34 | | 10.64 |
| LSD=0.05 | | LSD BC 1.514 | | | LSD B 0.689 | |
| | C | 9.22 | 11.72 | 10.96 | | LSD C 1.514 |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). *C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

Table 10: Effect of irrigation intervals, plant residues, and bio fertilization on the Percentage of total solid soluble in root of the beetroot.

| Percentage of total solid soluble (%) | | | | | | |
|---------------------------------------|---------------------|----------------------|-------|-------|-------|-------|
| Irrigation Intervals A | Plant Residues B | Bio fertilizers C | | | A*B | A |
| | | C1 | C2 | C3 | | |
| A1 | B1 | 13.20 | 13.97 | 13.43 | 13.53 | 12.48 |
| | B2 | 11.71 | 12.85 | 12.31 | 12.29 | |
| | B3 | 10.69 | 12.31 | 11.89 | 11.63 | |
| A2 | B1 | 11.06 | 12.05 | 11.53 | 11.55 | 10.72 |
| | B2 | 9.67 | 11.29 | 10.77 | 10.58 | |
| | B3 | 8.85 | 11.17 | 10.05 | 10.02 | |
| A3 | B1 | 7.36 | 7.85 | 7.51 | 7.57 | 7.90 |

| | | | | | | |
|----------|----|-------|---------------|-------|--------------|--------------|
| | B2 | 7.79 | 8.93 | 8.29 | 8.34 | |
| | B3 | 7.57 | 8.19 | 7.57 | 7.78 | |
| LSD=0.05 | | | LSD ABC 2.856 | | LSD AB 1.576 | LSD A 1.336 |
| | | | A*C | | | |
| | A1 | 11.87 | 13.04 | 12.54 | | |
| | A2 | 9.86 | 11.50 | 10.78 | | |
| | A3 | 7.57 | 8.32 | 7.79 | | LSD AC 1.751 |
| | | | B* C | | | B |
| | B1 | 10.54 | 11.29 | 10.82 | | 10.88 |
| | B2 | 9.72 | 11.02 | 10.46 | | 10.40 |
| | B3 | 9.04 | 10.56 | 9.84 | | 9.81 |
| LSD=0.05 | | | LSD BC 1.618 | | | LSD B 0.852 |
| | C | 9.77 | 10.96 | 10.37 | | LSD C 1.008 |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). *C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

Table 11: Effect of irrigation intervals, plant residues, and bio fertilization on the ascorbic acid in roots, mg/100 g fresh weight of the beetroot.

| Content of ascorbic acid in roots, mg/100 g fresh weight | | | | | | |
|--|----------------|-----------------|---------------|-------|--------------|--------------|
| Irrigation Intervals | Plant Residues | Bio fertilizers | | | A*B | A |
| | | C | | | | |
| | | C1 | C2 | C3 | | |
| A1 | B1 | 16.24 | 16.53 | 17.97 | 16.91 | 14.84 |
| | B2 | 13.01 | 13.75 | 14.81 | 13.86 | |
| | B3 | 13.49 | 13.54 | 14.19 | 13.74 | |
| A2 | B1 | 14.11 | 14.59 | 15.85 | 14.85 | 13.16 |
| | B2 | 11.93 | 12.47 | 13.53 | 12.64 | |
| | B3 | 11.56 | 11.96 | 12.41 | 11.98 | |
| A3 | B1 | 9.11 | 10.39 | 11.03 | 10.18 | 10.46 |
| | B2 | 9.97 | 10.91 | 12.57 | 11.15 | |
| | B3 | 9.75 | 9.93 | 10.45 | 10.04 | |
| LSD=0.05 | | | LSD ABC 3.233 | | LSD AB 1.621 | LSD A 0.629 |
| | | | A*C | | | |
| | A1 | 14.25 | 14.61 | 15.66 | | |
| | A2 | 12.53 | 13.01 | 13.93 | | |
| | A3 | 9.61 | 10.41 | 11.35 | | LSD AC 1.720 |
| | | | B* C | | | B |
| | B1 | 13.15 | 13.84 | 14.95 | | 13.98 |
| | B2 | 11.64 | 12.38 | 13.64 | | 12.55 |
| | B3 | 11.60 | 11.81 | 12.35 | | 11.92 |
| LSD=0.05 | | | LSD BC 1.942 | | | LSD B 1.111 |
| | C | 12.13 | 12.67 | 13.65 | | LSD C 1.176 |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). *C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

Table 12: Effect of irrigation intervals, plant residues, and bio fertilization on the Folic acid micro g. 100 g fresh weight in roots of the beetroot.

Content of Folic acid micro g. 100 g fresh weight

| Irrigation Intervals A | Plant Residues B | Bio fertilizers C | | | A*B | A |
|---------------------------|---------------------|----------------------|-------|-------|--------------|--------------|
| | | C1 | C2 | C3 | | |
| A1 | B1 | 367.0 | 375.3 | 399.1 | 380.5 | 360.4 |
| | B2 | 332.7 | 344.9 | 350.8 | 342.8 | |
| | B3 | 350.8 | 359.8 | 362.8 | 357.8 | |
| A2 | B1 | 338.4 | 346.5 | 360.4 | 348.4 | 331.3 |
| | B2 | 306.1 | 316.3 | 326.2 | 316.2 | |
| | B3 | 325.0 | 329.2 | 333.2 | 329.2 | |
| A3 | B1 | 218.4 | 228.3 | 237.4 | 228.0 | 227.4 |
| | B2 | 216.1 | 217.3 | 224.3 | 219.2 | |
| | B3 | 224.1 | 236.3 | 244.2 | 234.9 | |
| LSD=0.05 | | LSD ABC 56.29 | | | LSD AB 38.88 | LSD A 32.44 |
| A*C | | | | | | |
| A1 | | 350.2 | 360.0 | 370.9 | | |
| A2 | | 323.2 | 330.7 | 339.9 | | |
| A3 | | 219.5 | 227.3 | 235.3 | | LSD AC 36.02 |
| B* C | | | | | | |
| | B1 | 307.9 | 316.7 | 332.3 | | B 319.0 |
| | B2 | 285.0 | 292.8 | 300.4 | | 292.7 |
| | B3 | 300.0 | 308.4 | 313.4 | | 307.3 |
| LSD=0.05 | | LSD BC 31.68 | | | LSD B 21.35 | |
| | C | 297.6 | 306.0 | 315.4 | | LSD C 17.62 |

*A1: Irrigation according to the plant and soil's need for field capacity. A2 Irrigation 3 days after the plant and soil's need for field capacity. A3 Irrigation 6 days after the plant and soil's need for field capacity. *B1: Comparison treatment: NPK & Urea. B2: palm frond residues 40 ton. ha⁻¹ with (25% NPK and Urea) + B3 rice residues 40 ton. ha⁻¹ with (25% NPK and Urea). * C1: Control treatment (without addition) C2: Trichoderma 10 g. C3: Mycorrhizae 10 g.

4-Discussion

4.1. Impact of Irrigation Regimes

The results demonstrate a clear and significant advantage of optimal irrigation (A1) across most studied traits. Irrigation aligned with field capacity requirements helps maintain favorable plant water status by reducing the water potential gradient between the soil and atmosphere, thereby minimizing water loss through transpiration. This sustains cell turgor, which is fundamental for cell expansion, stomatal conductance, and the activation of enzymatic processes [11, 12]. Water serves as both a solvent and a reactant in biochemical pathways, directly influencing the synthesis of primary and secondary metabolites. Consequently, adequate soil moisture enhanced photosynthetic efficiency, leading to greater assimilate production. This was manifested in increased leaf area (Table 6), higher shoot dry matter (Table 7), and ultimately, superior root yield (Table 8). Furthermore, optimal water availability supported the biosynthesis of quality-related compounds, including betalain pigments, ascorbic acid, and folic acid (Tables 9, 11, 12), likely by facilitating the transport of

precursors and co-factors essential for their synthesis. Conversely, delayed irrigation (A2, A3) induced water stress, negatively impacting all measured parameters. Water deficit impairs chlorophyll synthesis and photosynthetic machinery, reduces carbon assimilation, and limits nutrient mobility and uptake from the soil [13, 14]. The resulting reduction in photoassimilates directly explains the observed declines in growth, biomass accumulation, and the concentration of soluble solids in storage roots. The lower leaf content of N, P, and K under deficit irrigation (Tables 3-5) further reflects restricted nutrient absorption and translocation under drought conditions.

4.2. Role of Nutrient Sources

The superior performance of the full chemical fertilizer treatment (B1) in several individual effects underscores the immediate nutrient supply advantage of soluble mineral fertilizers. Their rapid availability ensures a readily absorbable pool of N, P, and K during critical growth stages, supporting robust vegetative development and the synthesis of essential

biomolecules like amino acids and proteins [15, 16]. The synergistic relationship between these macronutrients is evident. Adequate nitrogen and phosphorus nutrition enhances potassium uptake and its physiological functions, which include osmoregulation, stomatal control, and the activation of enzymes involved in sugar transport and metabolism [17]. This integrated nutrient action promotes cell division, leaf expansion, photosynthetic capacity, and the translocation of carbohydrates to sink organs (roots), thereby improving both yield and quality attributes.

4.3. Mitigating Effects of Organic and Biological Amendment

A pivotal finding of this study is the capacity of integrated plant residue and bio-fertilizer applications to mitigate the adverse effects of water deficit. Under moderate irrigation delay (A2), combinations such as A2B2C2 or A2B3C3 frequently produced results for leaf nutrient content, growth, yield, and quality that were statistically on par with the optimal control (A1B1C1). This compensatory effect can be attributed to several interconnected mechanisms.

First, the incorporation of plant residues (palm frond, rice straw) improves soil physical properties, particularly water-holding capacity, thereby buffering the rhizosphere against rapid drying [18]. Second, these residues serve as a substrate for beneficial soil microbes. Bio-fertilizers like *Trichoderma spp.* enhance nutrient cycling and availability; they can solubilize fixed nutrients, produce phytohormones, and improve root health [19, 24, 25]. Mycorrhizal fungi (C3) extensively extend the root absorption surface area via extraradical hyphae, significantly improving the uptake of water and relatively immobile nutrients like phosphorus, especially under stress conditions [26, 27]. These fungi also secrete organic acids and phosphatase enzymes, converting unavailable nutrient forms into plant-accessible ones [28-30]. The improved nutritional status, particularly of nitrogen (Table 3), under these integrated treatments is crucial. Nitrogen is a fundamental component of amino acids (e.g., tyrosine, a precursor for betalain), proteins, and nucleic acids. Enhanced nitrogen nutrition, facilitated by microbial

activity and organic matter mineralization, likely drove the increased synthesis of betalain pigments (Table 9) and vitamins (Tables 11, 12) [20, 22, 23]. Similarly, the observed maintenance of total soluble solids (TSS) in roots under deficit irrigation with organic-biological combinations (Table 10) can be linked to improved potassium nutrition (Table 5), given potassium's key role in sugar translocation [21].

4.4. Synergistic Interactions and Practical Implications

The positive results from the three-way interaction treatments (e.g., A2B2C2, A2B3C3) highlight a synergistic effect. Plant residues improve the soil's physical and biological environment, which in turn enhances the establishment and efficacy of inoculated bio-fertilizers. Together, they create a more resilient rhizosphere that maintains nutrient and water availability during periods of irrigation delay. This synergy reduces the plant's dependence on both immediate irrigation and high doses of mineral fertilizers [31-33]. The findings align with previous research demonstrating that organic amendments and bio-fertilizers alleviate drought stress impacts by improving soil structure, microbial activity, and plant water-use efficiency [34-36]. From an applied perspective, this study suggests that in sugar beet cultivation under water-scarce conditions, applying 40 t ha⁻¹ of plant residues with a 75% reduction in chemical NPK fertilizer, combined with *Trichoderma* or mycorrhizal inoculation, can sustain productivity and quality even when irrigation is delayed by 3 days past field capacity. This integrated approach offers a viable strategy for sustainable intensification, contributing to water conservation, reduced chemical input, and enhanced system resilience.

5-Conclusions

This study demonstrates that optimal irrigation scheduling (irrigation at field capacity) coupled with full chemical fertilization provides the highest levels of growth, yield, and quality in sugar beet. However, this resource-intensive model presents challenges for sustainable agriculture in water-scarce environments. The

key finding is that the negative impacts of moderate water deficit (irrigation delayed by 3 days) can be effectively mitigated through an integrated soil management strategy. The application of plant residues (palm frond or rice straw at 40 t ha⁻¹) in combination with bio-fertilizers (Trichoderma or Mycorrhizae) successfully maintained leaf nutrient status, vegetative growth, root yield, and key quality parameters (betalain, TSS, ascorbic acid, folic acid) at levels statistically equivalent to those achieved under optimal irrigation and full chemical fertilization. This compensatory effect is attributed to the synergistic roles of organic amendments and beneficial microbes in enhancing soil water retention, improving nutrient cycling and availability (particularly nitrogen and phosphorus), and increasing plant stress tolerance. Consequently, this integrated approach—combining reduced irrigation, substantial mineral fertilizer reduction (75% NPK), and organic-biological inputs—proves to be a viable and sustainable alternative. Therefore, it is concluded that adopting integrated management practices, utilizing local plant residues and bio-fertilizers, can support productive and qualitative sugar beet cultivation while significantly conserving irrigation water and reducing dependence on chemical fertilizers, contributing to the sustainability of agricultural systems in arid and semi-arid regions.

6-References

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