Chemical and Bioactive Responses of Red Prickly Pear (*Opuntia ficus-indica*) Hybrid to Compost-Based Nutrition under Deficit Irrigation Levels

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Abstract

Prickly pear cactus (*Opuntia ficus-indica*) is increasingly promoted as a climate-resilient crop for semi-arid production systems. Yet, management options that jointly improve nutritional quality and water-saving management remain underexplored. This study presents an analysis of the red hybrid (R) from a multi-factor field experiment (Tikrit University, Iraq; March-October 2024), focusing on two factors: organic fertilization (M1: control; M2: 10% compost v/v; M3: compost tea, 10% monthly) and irrigation level (Fc1: 3 L, Fc2: 6 L, Fc3: 9 L plant^{-1} applied twice weekly). Young cladodes were analyzed for dry matter (DM), nitrogen (N), crude protein, P, K and Ca, as well as bioactive-physiological traits (total phenolics, total flavonoids, total chlorophyll and proline). Compost (M2) consistently increased N and protein under higher irrigation (Fc3), reaching 1.8267% N and 11.417% protein, while compost tea (M3) maximized K and Ca (2.8233% K and 7.67% Ca at Fc3). Deficit irrigation (Fc1) raised DM and antioxidant metabolites: M2Fc1 recorded the highest DM (15.851%) and total phenolics (160.43 mg 100 g^{-1}), whereas Proline accumulation under M1Fc1 (466.03 µg g^{-1} FW). Total flavonoids increased under deficit irrigation and peaked at M2Fc1 (33.57 µg g^{-1} FW), indicating osmotic adjustment under water limitation; organic amendments modulated stress-related metabolites while maintaining high phytochemical levels. Overall, compost-based nutrition combined with deficit irrigation offers a practical strategy to tailor cactus pear cladode quality to specific value chains (fresh pads vs. functional ingredients) while reducing irrigation volumes. These findings support using compost amendments and deficit irrigation to optimize nutraceutical value while sustaining mineral nutrition and reducing water inputs in semi-arid systems for resilient cactus pear production and processing.

Keywords: Cactus pear, compost tea, deficit irrigation, flavonoids, proline.

Introduction

Cactus pear (*Opuntia* spp.) is a crassulacean acid metabolism (CAM) crop well adapted to arid and semi-arid environments, with high water-use efficiency and the capacity to sustain biomass production under limited water availability [1,3]. In addition to its agronomic resilience and value as alternative fodder [2], *Opuntia* cladodes and fruits provide dietary fiber, minerals, and diverse bioactive phytochemicals (phenolics, flavonoids and betalains) with antioxidant and health-related potential [5,9]. Domestication history and morphological variability of *Opuntia ficus-indica* further support its adaptation across semi-arid regions [3,4].

In water-scarce production systems, irrigation management is a key lever to balance productivity and quality. Deficit irrigation can reduce water inputs, but it may induce physiological and metabolic adjustments that affect product quality, including changes in photosynthetic pigments and accumulation of compatible solutes such as proline [10,14]. Proline is a multifunctional metabolite involved in osmotic adjustment and stress tolerance and is widely used as an indicator of drought-related stress status [12,14]. Water deficit may also shift plant resource

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allocation toward defense and secondary metabolism, potentially increasing antioxidant metabolites such as phenolics and flavonoids [11,14].

Organic amendments such as compost, compost tea and vermicompost can improve soil structure, nutrient retention and microbial activity, thereby enhancing nutrient availability and buffering drought effects [15,18]. Compost tea provides readily available nutrients and microbial metabolites; its effects depend on preparation and application practices and have been reported for several horticultural crops under organic management [19,21]. In *Opuntia*, organic fertilization has been shown to modify mineral composition and quality attributes of young cladodes and related products, although responses depend on amendment type and management conditions [22,25]. Despite increasing cultivation interest in the Middle East, evidence under Iraqi semi-arid conditions—particularly for young cladodes and coloured hybrids—is still limited, and the interaction between compost-based nutrition and irrigation level remains underexplored.

Therefore, the present study aimed to quantify how compost and compost tea interact with irrigation level (3, 6, and 9 L plant^{-1} applied twice weekly) to influence the chemical composition (dry matter, N, crude protein, P, K and Ca) and key bioactive and physiological traits (total phenolics, total flavonoids, total chlorophyll and proline) of young cladodes of the red prickly pear hybrid under field conditions. It was hypothesized that compost-based amendments may enhance mineral nutrition under adequate irrigation, whereas deficit irrigation may increase dry matter and antioxidant-related metabolites; furthermore, organic amendments may modulate stress responses such as proline accumulation.

Materials and Methods

Experimental location and duration

The field experiment was conducted at the Department of Horticulture and Landscape, College of Agriculture, Tikrit University, Iraq, from 3 March to 1 October 2024. Uniform cladodes (approximately 30–35 cm) of prickly pear hybrids (R) were obtained from a commercial farm in Syria. The experimental soil was classified as sandy loam with pH 7.40, EC 2.32 dS m^{-1} and 1.60% organic matter (Table 2). Pads were collected from healthy, disease-free mother plants, surface-cleaned, treated with a fungicide, and transplanted to the field.

Field preparation

After land leveling, planting pits (30 × 30 × 40 cm) were prepared using a mechanical auger. Pits were filled according to the assigned growth medium, drip irrigation lines were installed, and the soil was pre-moistened. Cladodes of the red hybrid (R) were planted vertically at 1.5 m spacing. Basic soil properties are presented in Table 2.

Table 1. Physical and chemical properties of the compost

Property	Value
Nitrogen (N, %)	1.60
Phosphorus (P, %)	1.20
Potassium (K, %)	2.10
Calcium (Ca, %)	1.90
Iron (Fe, %)	0.43
Magnesium (Mg, mg kg^{-1})	84.50
Copper (Cu, mg kg^{-1})	37.40
pH	7.20
Organic matter (%)	46.00
Organic carbon (%)	26.40
C/N ratio	16.50

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Table 2. Physical and chemical properties of the experimental soil (0–30 cm)

Property	Value
Texture class	Sandy loam
Sand (%)	29.80
Silt (%)	51.40
Clay (%)	18.80
pH (1:1)	7.40
EC (dS m^{-1})	2.32
Organic matter (%)	1.60
$CaCO_3$ (%)	11.20

Experimental design and treatments

Treatments were arranged in a randomized complete block design with four replications. The red hybrid (R) was analyzed as a 3 × 3 factorial combining three organic fertilization and three irrigation levels (Fc1: 3 L; Fc2: 6 L; Fc3: 9 L $plant^{-1}$ per irrigation) delivered twice weekly via drip irrigation (1 L min^{-1} discharge per plant). The nine treatment combinations (M × Fc) are summarized in Table 3.

Table 3. Factor levels and treatment combinations

Treatment code	Organic fertilization (M)	Irrigation level (Fc)	Water applied (L $plant^{-1}$, twice weekly)
M1Fc1	Control (no organic addition)	Fc1	3
M1Fc2	Control (no organic addition)	Fc2	6
M1Fc3	Control (no organic addition)	Fc3	9
M2Fc1	Compost (10% v/v)	Fc1	3
M2Fc2	Compost (10% v/v)	Fc2	6
M2Fc3	Compost (10% v/v)	Fc3	9
M3Fc1	Compost tea (10% monthly)	Fc1	3
M3Fc2	Compost tea (10% monthly)	Fc2	6
M3Fc3	Compost tea (10% monthly)	Fc3	9

Young cladodes were sampled after six months of field establishment for chemical and bioactive analyses. Dry matter (DM) was determined gravimetrically after oven drying, and total N was quantified by Kjeldahl digestion following standard procedures [26,27]. Crude protein was calculated as N × 6.25 [26]. Phosphorus was determined by the Olsen method, and K and Ca were quantified using standard soil/plant analysis procedures [28,29]. Total phenolics were determined using the Folin–Ciocalteu assay and expressed as mg 100 g^{-1} fresh weight [30]. Total flavonoids were quantified by the aluminium chloride colourimetric method [31], and proline was measured following the ninhydrin-based method of Bates et al. [32]. Total chlorophyll was determined spectrophotometrically [33].

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Statistical analysis

Data were subjected to analysis of variance (ANOVA). Means were compared using the least significant difference (LSD) test at $P \leq 0.05$.

Results and Discussion

The chemical composition and physiological traits of young cladodes showed a clear interaction between organic fertilization and irrigation level (Tables 4 and 5). Treatment comparisons described as significant follow the corresponding $LSD_{0.05}$ values reported in the tables ($P <= 0.05$).

Table 4. indicates that cladodes number (plant^{-1}) was significantly influenced by the interaction between organic fertilization and irrigation ($LSD_{0.05}$=0.561). The lowest cladode number was recorded under deficit irrigation in the control (M1Fc1: 3.00), whereas higher values under compost and compost tea, reaching 5.33 cladodes plant^{-1} at M2Fc3, M3Fc2 and M3Fc3; these treatments were significantly higher than the control (3.00–3.67) because the differences exceeded $LSD_{0.05}$. The increase in cladode production under compost-based nutrition is consistent with the role of organic amendments in improving soil fertility, nutrient retention and microbial mineralization, thereby supporting vegetative growth and pad emission under field conditions [15,17], and aligns with the adaptive growth capacity of CAM cacti under improved resource availability [1,3,14]. Deficit irrigation (Fc1) consistently produced higher dry matter (DM, 15.49-15.85%) than Fc2 (12.34-12.52%) and Fc3 (11.99-12.35%). The highest DM was recorded at M2Fc1 (15.85%), which was comparable to M1Fc1 (15.73%) but significantly higher than M3Fc1 (15.49%). Conversely, the lowest DM occurred at M2Fc3 (11.99%). This increase in DM under Fc1 is consistent with a concentration (dilution) effect under water deficit in succulent CAM tissues, where reduced tissue hydration elevates the proportion of dry matter [14]. This response is consistent with the concentration effect commonly observed under water limitation in CAM succulents, where reduced tissue hydration and dilution can increase DM proportion in cladodes [11,14].

Nitrogen and crude protein increased under compost (M2), particularly when irrigation was higher (Fc3). The maximum N (1.83%) and protein (11.42%) were obtained at M2Fc3, which significantly exceeded the corresponding control at the same irrigation level (M1Fc3: 1.09% N and 6.81% protein) and was also higher than M2Fc2 (1.68% N; 10.50% protein). The lowest N and protein were observed under the control combined with deficit irrigation (M1Fc1: 0.85% N; 5.32% protein). Physiologically, improved N availability supports amino acid and protein synthesis, and compost can enhance nutrient retention and microbial mineralization, improving synchrony between nutrient release and plant uptake [15,17]. These patterns support the established role of compost in enhancing nutrient retention and microbial mineralization, thereby improving the synchrony between nutrient release and plant uptake under field conditions [15,17], in agreement with earlier Opuntia studies under organic nutrition [22,25].

Phosphorus reached its maximum at M2Fc3 (0.275%) and was similar to M3Fc3 (0.270%), while both treatments exceeded the lowest P recorded at M1Fc3 (0.175%). In contrast, compost tea (M3) was most effective for cation accumulation under higher irrigation: M3Fc3 produced the highest K (2.82%) and Ca (7.67%), and it was higher than M2Fc3 (2.32% K; 6.96% Ca). The lowest K and Ca were recorded at M1Fc1 (1.43%) and M1Fc3 (6.69%), respectively. This pattern is consistent with compost tea providing a more readily soluble nutrient fraction, which can enhance ion availability and uptake when water is not limiting [19,21]. The superiority of compost tea for K and Ca under Fc3 can be attributed to its soluble fraction and rapid

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nutrient availability when water is not limiting, as reported for compost tea applications in horticultural crops [19,21].

Table 5. shows that total chlorophyll was maximized by compost tea under moderate irrigation. The highest chlorophyll concentration occurred at M3Fc2 (1.212 mg g^{-1}), and it was slightly but significantly higher than M3Fc3 (1.206 mg g^{-1}). In contrast, the minimum chlorophyll content was observed under the control combined with deficit irrigation (M1Fc1, 0.706 mg g^{-1}). Physiologically, adequate mineral nutrition supports chlorophyll biosynthesis and maintenance of the photosynthetic apparatus under sufficient water supply, whereas drought stress can impair pigment stability and reduce chlorophyll content [14]. This suggests that improved nutrition combined with adequate water supply supports pigment maintenance and photosynthetic capacity under field conditions [12,14].

Regarding bioactive compounds, total flavonoids peaked under deficit irrigation with compost (M2Fc1: 33.57 mg 100 g^{-1}), exceeding the lowest value observed at M2Fc3 (24.87 mg 100 g^{-1}). Total phenolics followed a similar trend: the highest phenolics were recorded at M2Fc1 (160.43mg100 g^{-1}) and were significantly higher than M2Fc3 (158.83 mg 100 g^{-1}), whereas the lowest occurred at M1Fc2 (132.47 mg 100 g^{-1}); in addition, M1Fc1 (157.07) and M3Fc1 (157.33) were comparable. Mechanistically, water deficit can shift allocation from growth to defense and promote the accumulation of antioxidant secondary metabolites (phenolics/flavonoids) to counter oxidative pressure and protect cellular structures, consistent with the growth–defense concept [11,14] and with reports on *Opuntia* antioxidant potential [8,30]. Moreover, the higher DM under Fc1 may also contribute to an apparent increase in metabolite concentrations on a fresh-weight basis (a dilution/concentration component), acting in parallel with metabolic induction [14]. The enrichment of phenolics and flavonoids under Fc1 is consistent with the concept that water deficit can shift allocation toward protective secondary metabolism and antioxidant defence, particularly in drought-adapted CAM plants [11,14], and aligns with previous reports on the antioxidant potential of Opuntia cladodes [8,30].

Proline accumulation was greatest under deficit irrigation in the control treatment. The highest proline content was recorded at M1Fc1 (466.03 µg g^{-1} FW) and was significantly higher than M2Fc1 (436.06 µg g^{-1} FW), while the lowest value occurred at M1Fc3 (325.53 µg g^{-1} FW). Proline is a key compatible solute involved in osmotic adjustment and protection of proteins and membranes under drought stress; therefore, its increase under Fc1 reflects stress intensity [12,14]. The comparatively lower proline under organic amendments at the same irrigation level can indicate partial stress buffering through improved soil fertility and nutrient availability [15,17,22,25]. This confirms proline as a sensitive indicator of osmotic adjustment under water limitation [12,14] and suggests that organic amendments can modulate stress-related biochemical responses under the same irrigation regime [22,25].

From a management perspective, the data indicate that compost under higher irrigation (M2Fc3) is most suitable when the objective is to maximize N, crude protein and P, whereas compost tea under Fc2-Fc3 is preferred when the objective is to maintain higher chlorophyll and increase K and Ca. Conversely, deficit irrigation (Fc1) enhances DM and antioxidant-related metabolites, with M2Fc1 combining high DM (15.85%) and the highest flavonoids and phenolics. Overall, integrating compost-based nutrition with regulated irrigation offers a practical strategy to tailor the mineral and phytochemical profile of *Opuntia* cladodes under semi-arid conditions [22,25].

Table 4. Chemical composition of young cladodes of the red prickly pear hybrid (R) as affected by organic fertilization and irrigation level.

Treatment	Cladodes ($plant^{-1}$)	DM (%)	N (%)	Protein (%)	P (%)	K (%)	Ca (%)
M1Fc1	3.00	15.73	0.85	5.32	0.187	1.43	7.13
M1Fc2	3.67	12.34	1.22	7.65	0.183	1.47	7.18
M1Fc3	3.67	12.01	1.09	6.81	0.175	1.83	6.69
M2Fc1	4.33	15.85	1.25	7.81	0.21	1.71	7.33
M2Fc2	4.33	12.52	1.68	10.5	0.226	1.8	7.29
M2Fc3	5.33	11.99	1.83	11.42	0.275	2.32	6.96
M3Fc1	4.00	15.49	1.55	9.71	0.203	1.81	7.28
M3Fc2	5.33	12.47	1.69	10.56	0.228	1.96	7.05
M3Fc3	5.33	12.35	1.72	10.77	0.27	2.82	7.67
$LSD_{0.05}$	0.561	0.196	0.022	0.138	0.0054	0.079	0.029

* Two treatment means are significantly different when the difference between them is ≥ $LSD_{0.05}$ ($P \leq 0.05$).

Table 5. Bioactive and physiological traits of young cladodes of the red prickly pear hybrid (R) as affected by organic fertilization and irrigation level.

Treatment	Total chlorophyll (mg g^{-1})	Total flavonoids (mg 100 g^{-1})	Total phenolics (mg 100 g^{-1})	Proline (µg g^{-1} FW)
M1Fc1	0.706	31.73	157.07	466.03
M1Fc2	0.843	26.23	132.47	328.27
M1Fc3	0.874	28.63	135.47	325.53
M2Fc1	0.875	33.57	160.43	436.06
M2Fc2	1.105	28.53	152.97	325.57
M2Fc3	1.057	24.87	158.83	346.93
M3Fc1	1.054	31.73	157.33	395.06
M3Fc2	1.212	26.77	153.63	340.87
M3Fc3	1.206	26.27	157.47	345.37
$LSD_{0.05}$	0.0033	0.35	1.24	1.84

* Two treatment means are significantly different when the difference between them is ≥ $LSD_{0.05}$ ($P \leq 0.05$).

Conclusion

Compost-based nutrition and irrigation level jointly determined the chemical and bioactive profile of young cladodes of the red prickly pear hybrid. Compost (10% v/v) maximized N, protein and P, while compost tea enhanced K, Ca and chlorophyll under moderate-to-high irrigation. Cladode number ($plant^{-1}$) increased under compost-based treatments compared with the control, indicating a positive productivity-related response alongside quality improvement. Deficit irrigation (3 L $plant^{-1}$, twice weekly) increased dry matter and stress-related metabolites; M2Fc1 recorded the highest DM and total phenolics, whereas total flavonoids were highest under M1Fc1. These

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results support the use of targeted organic amendments together with regulated deficit irrigation to tailor cactus pear quality and improve water-saving management under semi-arid conditions.

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