Impact of Organic Fertilization on Morpho-Chemical Traits and Bioactive Compounds in Young *Opuntia Ficus-Indica* Hybrids

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Abstract
Organic amendments can enhance the early establishment of *Opuntia ficus-indica* under semi-arid conditions. This study evaluated the effects of two low-cost compost-based fertilization strategies: solid compost (10% v/v in planting pits) and compost tea (10% w/v fermented 48 h; applied monthly at 15% of pit capacity) on morphology, chemistry, and some bioactive of three prickly pear hybrids (red, white, honey) grown at the College of Agriculture, Tikrit University (April–October 2024) on a sandy loam soil. A strip–split RCBD with four replicates compared nine (hybrid × amendment combinations). Traits included plant height, cladode number and area, root traits, dry matter, ash, Nitrogen and crude protein, total chlorophyll, flavonoids, and proline. Relative to the unamended control, solid compost increased vegetative stature (e.g., plant height up to ~18% and cladodes per plant by ~56% in the red hybrid), while compost tea most strongly improved physiological quality (total chlorophyll to 1.157 mg g^{-1} and N to 1.78%, equivalent to 11.12% crude protein). Ash content rose to ~24–25% with either amendment. Flavonoids remained high (≈26.6–29.0 mg 100 g^{-1}), with genotype-specific responses, whereas proline declined from control levels (~360–373 mg 100 g^{-1}), indicating reduced stress. Many effects and hybrid × amendment interactions were significant (ANOVA; LSD, $p \leq 0.05$). We conclude that solid compost is preferable when structural growth is prioritized, whereas compost tea better enhances leaf biochemistry; hybrid choice further modulates.

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Keywords: *Cactaceae*, Cladodes, Prickly Pear, Tea Compost

1. Introduction

Opuntia ficus-indica (prickly pear cactus) is a CAM succulent from the *Cactaceae* family, native to Mexico and now widely grown across Africa, the Mediterranean, and the Americas, valued for it is resilience to heat and drought [1]. CAM physiology confers high water-use efficiency and drought tolerance, positioning *O. ficus-indica* as a climate-resilient crop for regions with erratic rainfall or limited irrigation [2, 3]. Historically cultivated for cochineal, *O. ficus-indica* is now valued as a sustainable dryland crop for its efficiency in converting scarce water into substantial biomass and yield under harsh conditions [2, 3]. While fruit is well known, cladodes are equally pivotal in arid systems as both food and fodder: they are eaten as a vegetable and used as drought-season feed [3]. Nutritionally, cladodes provide substantial dietary fiber, minerals, vitamin C, amino acids, and phenolic/flavonoid profiles that confer antioxidant capacity often comparable to conventional vegetables in juvenile pads, supporting their functional-food value [1,4,5,6,7]. Additionally, Opuntia extracts are used in pharmaceutical and cosmetic formulations for their antioxidant, anti-inflammatory, and moisturizing activities [8, 9]. Intensive reliance on synthetic NPK threatens long-term soil health: it reduces soil organic matter, disrupts microbial communities, and degrades structure and fertility, while emissions and off-site losses further undermine sustainability, particularly in fragile drylands [10, 11]. Rising input costs, an imperative, have therefore accelerated the shift toward organic fertility management. Organic fertilization provides a biologically grounded alternative by recycling organic residues as soil amendments, improving soil condition while supplying nutrients gradually and ecologically [12]. Well-decomposed compost raises stable soil organic matter and enhances structure, water retention, and cation-exchange capacity, key traits for sandy, nutrient-poor drylands; it releases nutrients slowly via mineralization, moderating losses and sustaining plant nutrition, while stimulating soil biota, enzyme activity, and nutrient cycling with ancillary disease-suppressive effects [2, 10, 11, 13]. As a complementary approach, compost tea, an aqueous extract/brew rich in soluble organics and beneficial microbes, can be applied as a soil drench or foliar spray to deliver readily available nutrients and microbial consortia at the plant soil interface; evidence shows it enhances nutrient uptake and growth and can suppress certain foliar and soil-borne pathogens via antagonism and competition. More broadly, compost and compost tea emulate natural nutrient cycling, improving seedling establishment, vegetative vigor, yield, and product quality while reducing reliance on synthetic inputs [14, 15]. For cactus crops on marginal, low-fertility soils, organic inputs are advantageous [2]. Across *Opuntia* systems, compost increases vegetative propagation, yield, and quality and can extend productive lifespan, while mitigating drought and enhancing shoot production [16, 17]. Vermicompost and biofertilizers also elevate cladode nutraceutical and physiological traits, boosting phenolics, flavonoids, antioxidant capacity, sugars, vitamin C, and chlorophyll, indicating that compost-based (solid or liquid) fertilization can jointly enhance morphology and internal chemistry [4,18]. Despite advances in organic fertilization research, juvenile *O. ficus-indica*, especially hybrids, remain poorly characterized; most work focuses on mature orchards under mineral or raw-manure regimes [2]. This study tested whether compost and compost tea improve early morphology and cladode chemical and bioactive profiles in juvenile *O. ficus-indica* hybrids compared with an unfertilized control, and whether responses differ among hybrids. It was hypothesized that organic inputs would promote early growth, enrich mineral and bioactive contents, and exhibit genotype-dependent effects, particularly since the crop is being cultivated for the first time in this region

2. Materials and Methods

2.1. Experimental Location and Duration

The experiment was conducted at the open experimental farm of the College of Agriculture, Tikrit University, Iraq (34.6158° N, 43.6786° E) from April 1, 2024, to October 1, 2024. The study evaluated three *Opuntia ficus-indica* (prickly pear) hybrids under organic fertilization treatments using solid compost and compost tea (liquid compost). The effects of these additions on the three hybrids were assessed by measuring plant morphological traits, biochemical characteristics, and selected bioactive compounds.

2.2. Plant Source and Preparation

Cladodes (pads) of three *Opuntia ficus-indica* hybrids [Red (R), White (W), and Honey (H)] were obtained from a commercial farm in Syria for the purpose of testing their cultivation in the region for the first time. The cladodes were excised from mature, healthy, and infection-free mother plants of high commercial quality. Uniform pads (30–35 cm in length) were treated with a fungicide before transplanting into the field.

2.3. Field Preparation

The experimental field was prepared by levelling the land, followed by digging planting pits using a mechanical auger. Each pit measured 30 × 30 × 40 cm and was filled with the designated growth medium according to the experimental treatments. Drip irrigation lines were subsequently installed, and the soil was moistened before planting to ensure favourable conditions for establishment. The hybrids cladodes were planted vertically in the prepared medium. The planting distance was maintained at 1.5 m between plants. The physical and chemical characteristics of the field soil used for cultivation are presented in Table 1.

Table 1: Chemical properties of soil in the experiment.

pH	EC (dS m^{-1})	N (ppm)	P (ppm)	K (ppm)	Zn (ppm)	O.M. (%)	Gypsum (%)	$CaCO_3$ (%)
7.4	2.32	12.3	11.2	29.5	1.26	1.6	6.8	21.3

2.4. Experimental Design and Treatments

The field experiment followed a Randomized Complete Block Design (RCBD) arranged in a strip–split plot arrangement with four replications. The experiment was arranged as a one-way design consisting of nine treatment combinations obtained by combining three *Opuntia ficus-indica* hybrids *:*Red (R), White (W), and Honey (H), with three compost application methods, M1: planting in field soil without organic amendment (control), M2: 10% (v/v) solid compost, prepared by mixing nine parts field soil with one part compost (1:9), homogenized and placed in the planting pit as the growth medium, M3; compost tea at 10%, prepared at 1:9 (compost:water), fermented for 48 h with twice-daily stirring, and applied monthly at a volume equivalent to 15% (v/v) of the planting-pit capacity. In a one-way framework, nine hybrids × compost-method combinations were evaluated; each combination was treated as a single treatment level, as shown in Table 2.

Table 2: Hybrid × compost-method treatment combinations (one-way design).

Treatment	Hybrid	Compost method
T1	R	M1
T2	R	M2
T3	R	M3
T4	W	M1
T5	W	M2
T6	W	M3
T7	H	M1
T8	H	M2
T9	H	M3

2.5. Statistical Analysis

Treatment effects were tested by one-way ANOVA, and mean comparisons were performed using the Least Significant Difference (LSD) test at the 0.05 probability level.

2.6. Studied parameters

The studied parameters included morphological traits: plant height (cm), number of cladodes per plant, cladode area (cm²), root length (cm), and root number per plant. Chemical traits: dry matter (%) [19]. total nitrogen (%) by the micro-Kjeldahl method [20]. crude protein (%) calculated as Protein = N × 6.25 [21]. ash content (%) [22]. and total chlorophyll [23]. Bioactive compounds: total flavonoids [24]. and proline [25].

3. Results

Data in Table 3 show that organic fertilization improved most vegetative traits relative to the unfertilized control across hybrids. Plant height was maximized in the Red × solid compost combination (T2, 54.00 cm vs. 45.78 cm in the Red control, T1), while the remaining hybrid treatment means ranged 46.78–53.44 cm; differences ≥1.484 cm were significant at $LSD_{0.05}$. The number of cladodes per plant likewise increased under organic inputs, with T2 reaching 4.33 compared with 2.77 in T1 ($LSD_{0.05}$ = 0.561). Cladode area responded positively, particularly in the White hybrid under compost tea (T4, 130.89 cm²; $LSD_{0.05}$ = 2.311). Root length exhibited modest gains under organic fertilization (maximum 42.63 cm in T2; $LSD_{0.05}$ = 0.581), whereas root number peaked in the Honey control (T7, 22.22) and was generally reduced or maintained by organic treatments ($LSD_{0.05}$ = 0.675), suggesting a shift in allocation toward above-ground growth when nutrients are more readily available.

Results in Table 4 show that dry matter content was not significantly affected by treatment (13.11–13.45%; $LSD_{0.05}$ = 0.1904). In contrast, ash content increased consistently under organic fertilization (≈24.14–24.49%) relative to the controls (21.32–21.84%), indicating greater mineral accumulation. Total nitrogen increased from 1.05–1.17% in controls to 1.58–1.78% with organic inputs, corresponding to higher crude protein levels (6.60–7.36% vs. 9.91–11.12%). Total chlorophyll also rose under organic management, reaching 1.157 mg g⁻¹ in T3 compared with ≈0.808–0.841 mg g⁻¹ in control T1; differences as small as 0.00307 mg g⁻¹ were statistically significant at $LSD_{0.05}$. Taken together, Table 4 demonstrates that organic fertilization improves the nutritional status of cladodes (N, protein, ash) and enhances photosynthetic capacity (chlorophyll).

Table 3: Effect of Hybrid × compost-method treatment combinations on some morphological parameters

Treatments	Means Plant Height (cm)	Means Number of Cladodes per Plant	Means Cladode Area (cm²)	Means Root Length (cm)	Means Roots Number per Plant
T1	45.78	2.77	99.61	39.61	20.78
T2	54.00	4.33	123.37	42.63	19.00
T3	53.44	3.66	129.45	42.50	21.56
T4	46.78	2.88	103.36	38.64	20.78
T5	52.33	3.44	123.27	41.76	19.67
T6	51.67	3.11	130.89	40.02	19.56
T7	49.67	2.87	103.17	39.37	22.22
T8	51.00	3.44	128.39	41.98	18.22
T9	50.22	3.11	129.59	40.89	19.00
$LSD_{0.05}$	1.484	0.561	2.311	0.581	0.675

*Two treatment means are significantly different when the difference between them ≥ $LSD_{0.05}$

Table 4: Effect of Hybrid × Compost-Method treatment combinations on some chemical parameters

Treatments	Parameters				
	Means Dry Matter %	Means Ash %	Means Nitrogen %	Means Protein %	Means Total Chlorophyll (mg g⁻¹)
T1	13.36	21.32	1.05	6.60	0.808
T2	13.45	24.14	1.58	9.91	1.013
T3	13.44	24.28	1.65	10.35	1.157
T4	13.11	21.63	1.17	7.36	0.83067
T5	13.29	24.17	1.76	11.01	1.044
T6	13.32	24.49	1.71	10.71	1.091
T7	13.17	21.84	1.13	7.06	0.841
T8	13.35	24.16	1.68	10.49	1.074
T9	13.24	24.14	1.78	11.12	1.025
$LSD_{0.05}$	0.1904	0.0158	0.02942	0.1839	0.00307

*Two treatment means are significantly different when the difference between them ≥ $LSD_{0.05}$

Across the same experimental contrasts, total flavonoids ranged 26.567–28.989 mg 100 g⁻¹ ($LSD_{0.05}$ = 0.3609), with the T2 (Red hybrid under solid compost) exhibiting the upper bound (28.989 mg 100 g⁻¹) and T8 (Honey under solid compost) the lower bound (26.567 mg 100 g⁻¹). Proline varied from 360.02 to 373.28 mg 100 g⁻¹ ($LSD_{0.05}$ = 1.737), tending to be higher in the unfertilized controls (e.g., T1, 373.28 mg 100 g⁻¹) and generally reduced by organic inputs, consistent with mitigation of osmotic stress in better-nourished plants.

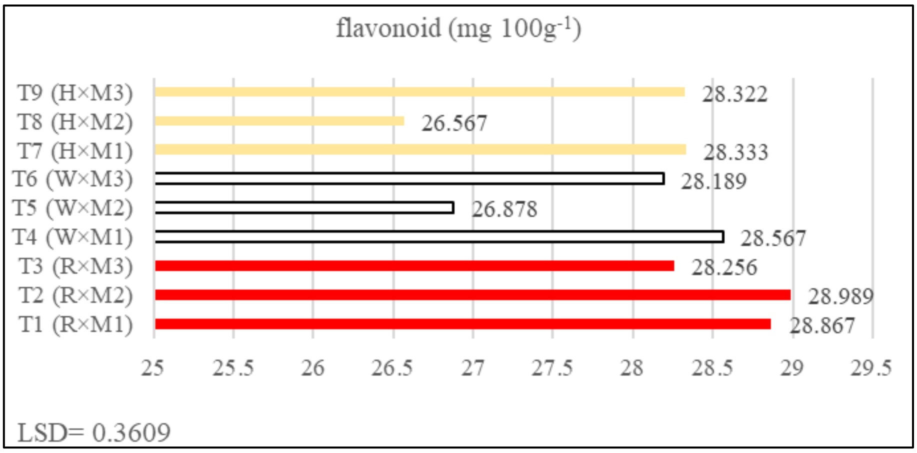

Fig 1: Effect of Hybrid × compost-method treatment combinations on flavonoid percentage in cladodes.

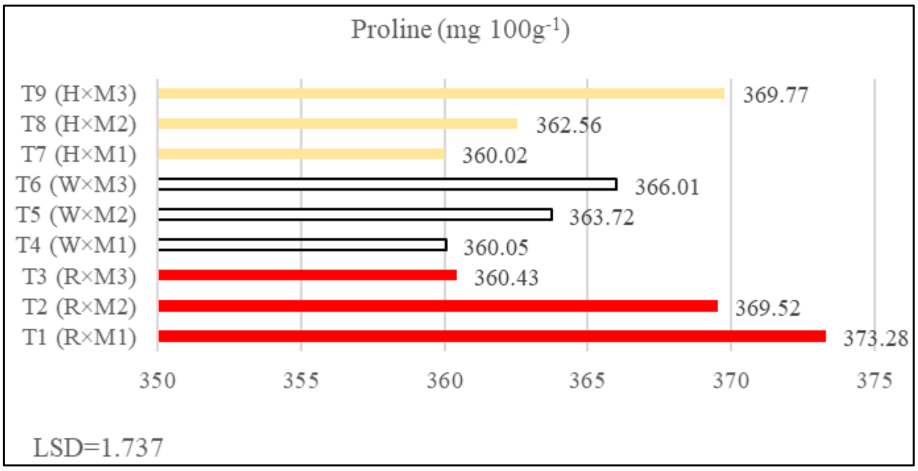

Fig 2: Effect of Hybrid × compost-method treatment combinations on proline content in cladodes.

4. Discussion

The study demonstrated that organic fertilization, particularly solid compost at 10% v/v, generally enhanced morphological performance in *O. ficus-indica* hybrids. Gains in plant height and cladode number were most pronounced in the Red hybrid, suggesting that sustained nutrient release from incorporated organic matter supported energy-intensive cladode differentiation. Such outcomes are consistent with reports that compost improves structural growth through continuous mineralization and enhanced soil physical properties, which are especially beneficial for slow-growing CAM succulents [26, 27, 28]. Genotype-specific responses, such as the larger cladode area observed in White under compost tea, highlight inherent differences in nutrient uptake efficiency and morphological plasticity among hybrids, aligning with earlier evidence of marked accession variability in *Opuntia* [29, 30].

Chemical composition analyses further confirmed the advantages of organic inputs. Ash content increased consistently under both compost and tea, reflecting greater mineral accumulation, plausibly mediated by higher cation exchange capacity and chelation processes that enhance nutrient bioavailability [31]. Total nitrogen and crude protein rose by approximately 50–67% compared to controls, in line with the provision of combined fast-and slow-release nitrogen forms and improved rhizosphere activity [32, 33, 34]. Elevated chlorophyll levels, 22–43% above controls, are interpretable as a consequence of enhanced N and Mg supply, consistent with chlorophyll biosynthesis [4, 35]. Collectively, these changes point toward improved photosynthetic capacity and nutritional quality of juvenile cladodes.

Bioactive compounds exhibited more nuanced patterns. Flavonoid concentrations varied strongly by genotype: the Red hybrid maintained high levels across treatments, whereas White and Honey tended to decline under solid compost. This is in agreement with previous findings that secondary metabolite accumulation in *Opuntia* is strongly influenced by both genotype and environmental conditions [36, 37, 38]. Such reductions are interpretable under the growth–differentiation balance hypothesis, which proposes that improved nutrient availability favours allocation toward growth at the expense of secondary metabolism [39]. Proline, a well-known osmolyte linked to abiotic stress, was highest in unfertilized controls and generally declined under organic management, consistent with stress alleviation under improved nutritional conditions [40, 41, 42].

Correlation analyses further support these interpretations. A negative association between N and proline ($r = -0.312$, $p < 0.05$) suggests that enhanced N status reduces the requirement for osmotic adjustment. Conversely, the weak positive association between flavonoids and chlorophyll ($r = 0.184$) indicates that improvements in photosynthetic apparatus may coincide with modest increases in secondary metabolism, although the strength of this relationship was limited. Such trade-offs and partial synergies emphasize the complexity of balancing primary growth processes with biochemical quality.

From a practical perspective, the results suggest that solid compost is preferable when the objective is to maximize structural growth, particularly in hybrids such as Red, whereas compost tea provides meaningful contributions to chlorophyll accumulation and, in some cases, N enhancement. The hybrid-dependent responses observed here underscore the importance of tailoring fertilization strategies: solid compost can be prioritized for architectural vigor, while compost tea may be leveraged to promote biochemical attributes in genotypes like White. Moreover, improvements in mineral and protein content enhance the fodder and nutritional value of juvenile cladodes, highlighting the dual agronomic and food–feed potential of *O. ficus-indica* under organic management [43, 44].

5. Conclusion

Organic fertilization substantially improved the early morpho-chemical performance of juvenile *Opuntia ficus-indica* hybrids compared with the unfertilized control. Across genotypes, incorporated solid compost delivered the most consistent gains in structural growth, particularly plant height and cladode number, while both solid compost and compost tea increased cladode area and root length, with hybrid-specific magnitudes of response. Chemically, organic management enhanced nutritional status (higher N, crude protein, and ash) and chlorophyll content, pointing to greater photosynthetic capacity. In parallel, proline concentrations tended to decline under organic inputs relative to controls, consistent with reduced osmotic stress in better-nourished plants, whereas total flavonoids were maintained within a relatively narrow range but showed hybrid- and treatment-specific peaks (e.g., Red hybrid under solid compost). Collectively, these results indicate that organic fertilization supports both growth and metabolic balance in juvenile cladodes, with the solid compost treatment providing the most robust overall benefits.

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