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Irrigation Levels, Biochar and Cultivars Effects on Soil Physical Properties and Growth of Lettuce (*Lactuca sativa* L.)

[1]Huda F. S. ALsardar, *[1]Fathel F. R. Ibraheem, [1]Ahmed Khairuldeen Abdulsalam

About Article

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About Author
[1] Soil Science and Water Resource, Faculty of Agriculture and Forestry, University of Mosul, Iraq

Contact @ Fathel F. R. Ibraheem
fathelffr@uomosul.edu.iq

ABSTRACT

A field experiment was undertaken during the 2024–2025 cropping season within the eco-touristic forest site affiliated with the College of Agriculture and Forestry, University of Mosul, aiming to elucidate the interactive effects of deficit irrigation, biochar soil amendment, and varietal differences on growth and physiological responses of lettuce (*Lactuca sativa* L.). The experimental framework was structured as a factorial arrangement embedded within a split-plot system under a randomized complete block design (RCBD). Main plots were assigned to two distinct cultivars of imported lettuce (Rama and Nader), while sub-plots were factorial arranged to accommodate three irrigation regimes 50%, 75%, and 100% of field capacityand two biochar application levels (0% and 0.5% w/w). Biochar, produced from a designated biomass feedstock, was incorporated into the soil matrix during the pre-transplantation phase. The experimental matrix comprised 12 treatment combinations (3 irrigation × 2 biochar × 2 cultivars) replicated thrice, yielding a total of 36 experimental units. Statistical evaluations were conducted following the prescribed design structure, and mean comparisons were executed using Duncan's Multiple Range Test at a 5% probability threshold ($p \leq 0.05$). The results demonstrated that biochar application at 0.5% significantly enhanced several soil physical indices, notably increasing the liquid limit, plastic limit, mean weight diameter (MWD), and aggregate stability. Parallel improvements were recorded in physiological traits, including elevated leaf chlorophyll concentrations, increased dry matter accumulation. Additionally, irrigation regimes set at 75% and 100% of field capacity consistently outperformed the 50% level in all measured vegetative and physiological traits. Notably, the Rama cultivar exhibited superior performance over Nader, particularly in chlorophyll content and plant stature, suggesting inherent genotypic advantages under the tested conditions.

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1. INTRODUCTION

Lettuce (*Lactuca sativa* L.) stands as one of the foremost vegetable crops within the family Compositae also scientifically designated as Asteraceae, commonly referred to as the Sunflower family (Hassan, 2003). This botanical family is recognized among the largest plant taxa, encompassing approximately 800 genera and exceeding 20,000 species, predominantly comprising annual herbaceous plants. Lettuce cultivation primarily targets the harvest of its tender foliage, consumed predominantly in fresh form (Kim *et al.*, 2016). The growth efficacy and yield potential of lettuce are influenced by a myriad of factors, chief among them prevailing climatic conditions in the cultivation locale and the extent to which optimal agronomic practices are implemented. Consequently, intensifying lettuce production per unit area through innovative agronomic techniques is imperative to enhance both yield quantity and quality. Global scarcity of water resources exacerbated by escalating demand and degradation in water quality poses a critical challenge, intensified further by climatic variability which imperils sustainable development sectors, especially agriculture. Thus, the adoption of advanced irrigation technologies coupled with regulated water use has become indispensable. Among contemporary agricultural water management strategies, deficit irrigation emerges as a pivotal approach aimed at conserving water by supplying crops with amounts sufficient to meet physiological demands while avoiding excess exploitation of hydric resources (Farooq *et al.*, 2019). Irrigation, in this context, is fundamental to securing food production and sustaining water resources, particularly in arid and semi-arid environments, where population growth and diminishing natural reserves heighten the urgency for enhanced water use efficiency (FAO, 2023). Within the spectrum of irrigation modalities, drip irrigation has garnered acclaim as a precision technique delivering water directly to the rhizosphere with minimal losses through surface runoff and evaporation, thereby markedly improving overall water use efficiency indices (Howell, 2001).

2. LITERATURE REVIEW

Performance reviews have underscored the criticality of regulating irrigation regimes based on percentages of field capacity, with varying thresholds employed to balance water conservation and high productivity (Fereres & Soriano, 2007). Additionally, diverse investigations into drip irrigation under variable environmental parameters have concluded that boosting agricultural water productivity demands not only technical efficiency but also the integration of research insights and practical application to bolster food security amid evolving climatic challenges (Kang *et al.*, 2017). Biochar a carbonaceous amendment derived from the pyrolytic decomposition of organic substrates under oxygen-limited conditions (anaerobic pyrolysis) has been extensively employed to enhance the physical properties of agricultural soils. Empirical evidence from numerous studies underscores biochar's capacity to modify key soil physical parameters, including bulk density, porosity, and saturated hydraulic conductivity. Its application has been associated with bulk density reductions that facilitate improved aeration and water retention within the soil profile (Lehmann *et al.*, 2011). Moreover, biochar positively influences Atterberg limits, specifically the liquid and plastic limits, thereby augmenting soil resistance to compaction and enhancing aggregate stability factors critical for erosion control and structural integrity (Mukherjee & Lal, 2013). Furthermore, biochar amendments have been linked to increases in the mean weight diameter of soil aggregates, reflecting a more favorable particle size distribution and improved soil texture (Agengehu *et al.*, 2016). Regarding plant responses, biochar incorporation into soil has demonstrably promoted vegetative growth and yield enhancement in lettuce, primarily through improvements in soil fertility, nutrient availability, and moisture conditions within the rhizosphere, culminating in increased biomass accumulation and total crop yield (Liu *et al.*, 2013). Collectively, biochar represents a sustainable and environmentally benign strategy for soil quality amelioration and agricultural productivity enhancement. The selection of an appropriate lettuce cultivar constitutes a critical determinant in defining both the quantity and quality of the yield, as cultivars exhibit intrinsic variations arising from the interplay between genetic factors and the surrounding environmental conditions. In Iraq, the majority of cultivated varieties, whether indigenous or imported, belong to the Cos or Romaine group, characterized by their elongated heads and distinctive productive traits (Carini *et al.*, 2020). Research indicates that the genetic attributes of the cultivated cultivar exert a profound influence on production performance in terms of both quantity and quality (Kumar *et al.*, 2000). Recent investigative efforts have been directed towards enhancing agricultural productivity by adopting high-efficiency vegetable cultivars, whether hybrid or pure lines. Differences in yield per unit area among cultivars primarily stem from their genetic potential and their interaction with environmental factors throughout the growth and fruiting stages (Ibraheem, 2007). This investigation was conceived to elucidate the impacts of employing drip irrigation strategies at varying proportions of field capacity, coupled with the incorporation of biochar amendments into the soil, alongside the selection of specific lettuce cultivars, on growth parameters and productivity metrics. Additionally, the study aimed to assess the influence of biochar application on the soil's physical attributes, striving to establish an optimal balance between enhancing crop yield quality and improving soil physical properties.

3. METHODOLOGY

The study encompassed three experimental factors: the first factor involved three drip irrigation levels 50%, 75%, and 100% of field capacity; the second factor comprised two biochar application rates (0% and 0.5% by weight); and the third factor included two imported lettuce cultivars (Nader and Rama). Biochar was incorporated into the soil during land preparation prior to seedling transplantation. Consequently, the experiment consisted of 12 treatment combinations (3 × 2 × 2) per replicate, replicated thrice, resulting in a total of 36 experimental units. The experimental layout was implemented as a factorial arrangement within split-plots under a randomized complete block design (RCBD), wherein the cultivars were allocated to the main plots, and irrigation levels alongside biochar treatments were randomized within the subplots. The trial was conducted in an open field located within the ecotourism forest area affiliated with the College of Agriculture and Forestry at the University of Mosul during the 2024–2025 growing season. Soil samples were collected from the 0–30 cm surface layer for the assessment of selected physical and chemical properties pertinent to the greenhouse soil substrate. Land preparation involved initial tillage using a disc plow, followed by homogenization and leveling with a harrow. The experimental field was subdivided into plots measuring 1.5 m in length by 1 m in width, resulting in a plot area of 1.5 m^2. Each plot contained three planting rows with intra-row spacing of 30 cm and inter-row spacing of 35 cm, accommodating 15 plants per plot and a total of 45 plants per treatment. A 50 cm isolation buffer was maintained between experimental units to prevent cross-contamination. Subsequently, drip irrigation lines—the irrigation method adopted for this study—were installed. Seeds of the two lettuce cultivars were procured: Rama, supplied by Prims Seeds (Netherlands) with 99% purity and 95% germination rate, classified as Romaine lettuce per the supplier's label; and Nader, provided by Enza Zaden (Netherlands) with 99% purity and 85% germination rate, also classified as Romaine lettuce. Sowing occurred on December 14, 2024, using plastic seedling trays containing 50 cells filled with peat moss as the growth medium. Seedlings were carefully transplanted on January 11, 2025, at the three- to four-leaf stage, maintaining peat moss around roots and ensuring adequate soil moisture. Cultural practices including fertilization, weeding, and preventive pest and disease control were uniformly applied across all experimental units. Urea fertilizer (46% N) was applied at 200 kg ha^{-1}, potassium sulfate (50% K_2O) at 200 kg ha^{-1}, and triple superphosphate (P_2O_5) at 300 kg ha^{-1}. Fertilizers were administered in a single dose one week post-transplanting via trenches dug alongside plants, followed by covering the fertilizer with soil (Hassan, 2003). Disease management included the application of Speed 24 SC, a systemic fungicide used to prevent and treat soil-borne diseases affecting vegetables and fruit trees, including root and stem rot, applied at 3–5 kg per dunam before planting. Additionally, Amidal 20 SL was sprayed at 1.5 ml L^{-1} as a protective measure against soil fungi causing seedling wilt and root rot. Statistical analyses were performed using the SAS software package (2017). Mean comparisons were conducted employing Duncan's Multiple Range Test at a significance level of 0.05 (Al-Rawi & Khalaf Allah, 2000). The following traits were evaluated:

i. Atterberg limits: The moisture content at the liquid limit was determined using the Atterberg device, while the plastic limit was assessed by rolling soil paste threads with a diameter of 3 mm. The plasticity index was subsequently calculated. Additionally, the effect of biochar addition on soil aggregate stability (%) was evaluated.

ii. Mean weight diameter (MWD): This parameter was used to express soil aggregate stability by employing the dry sieving method, as described by Kemper and Rosenau (1986).

iii. Leaf chlorophyll content (SPAD): The relative chlorophyll content in the leaves was estimated using the SPAD-502 chlorophyll meter, a device of Japanese origin. Six readings were taken per experimental unit, and the average value was subsequently calculated.

iv. Plant height (cm $plant^{-1}$): Plant height was measured from the soil surface to the apex of the uppermost leaf using a measuring tape.

v. Percentage of dry matter in leaves: Fresh weight samples were collected from plants within each experimental unit for every replicate. These samples were then dried to constant weight, after which the percentage of dry matter in the leaves was calculated using the following formula:

Percentage of dry matter in leaves = (Dry weight of sample/ Fresh Weight of Sample) * 100

4. RESULTS AND DISCUSSION

4.1. Effect of biochar addition on liquid limit, plastic limit, plasticity index (%), and clay activity

The results presented in Figures 1 and 2 indicate that the incorporation of biochar into the soil led to an increase in the gravimetric water content at both the liquid and plastic limits. As shown in the figures, the gravimetric water content at the liquid and plastic limits prior to biochar application was 40.68% and 29.10%, respectively. However, following the addition of biochar at a rate of 0.5%, these values increased to 43.52% and 30.84%, respectively. This increase may be attributed to the enhanced water retention capacity and the greater adhesive forces between soil particles and water resulting from biochar incorporation. These modifications tend to increase the plasticity and flexibility of the soil, making it more responsive to moisture variations particularly in clay-rich or organically enriched soils as reported by Mukherjee and Lal (2013).

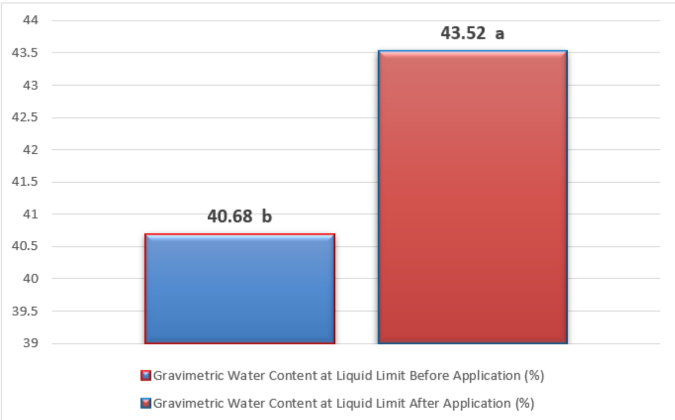

Figure 1. effect of biochar addition on gravimetric water content at the liquid limit before and after application

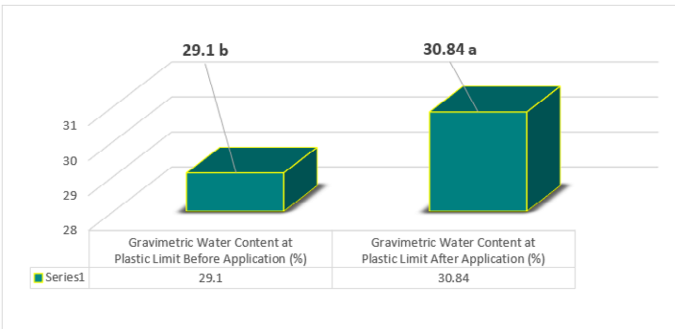

Figure 2. effect of biochar addition on gravimetric water content at the plastic limit before and after application

The results illustrated in Figures 3 and 4 reveal changes in the plasticity index and clay activity before and after biochar amendment. Initially, the plasticity index and clay activity values were recorded at 11.59% and 0.23, respectively, under control conditions (no biochar addition). Following the incorporation of biochar into the soil, these values increased to 12.68% for the plasticity index and 0.25 for clay activity. This enhancement can be attributed to the presence of reactive surface functional groups on biochar, such as carboxyl and hydroxyl moieties, which interact with clay particles and the surrounding water molecules. Such interactions expand the spacing between clay platelets and promote their swelling in aqueous environments, thereby elevating the clay's activity. These physicochemical dynamics result in a more plastic soil behavior post-biochar application, a phenomenon corroborated by Novak *et al.* (2009). Furthermore, biochar is characterized by its abundant colloidal-like properties, reflected in its high specific surface area and chemical reactivity, which collectively contribute to augmenting clay activity. An increased concentration of active colloidal materials within the soil enhances the clay's capacity to retain water and fosters the development of a more plastic soil structure (Glaser *et al.*, 2002). Additionally, biochar application elevates soil organic carbon content, a factor influencing soil texture and consistency. The organic carbon associates closely with clay particles, improving their flexibility in moist conditions, which translates into an increased plasticity index and improved soil molding and plastic deformation characteristics (Agegnehu *et al.*, 2016).

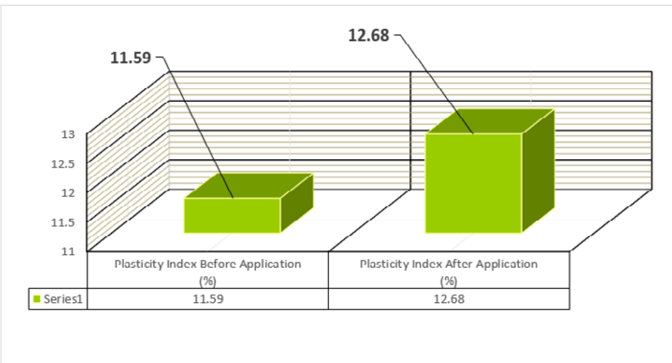

Figure 3. Effect of biochar addition on plasticity index

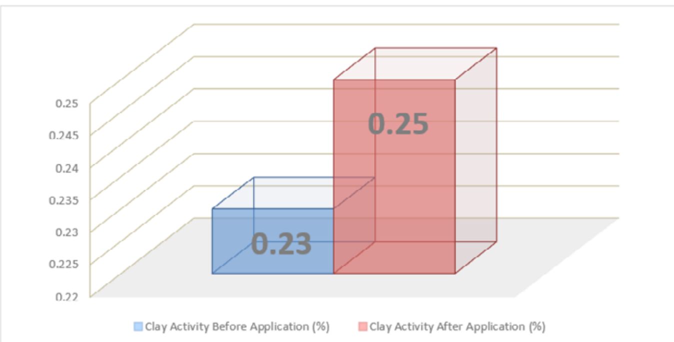

Figure 4. Effect of biochar addition on clay activity

4.2. Effect of biochar addition on soil aggregate stability (%)

Soil Aggregate Stability, a key indicator of structural soil quality, reflects the soil's capacity to resist disintegration under hydrological or mechanical stress. The findings illustrated in Figure 5 demonstrate a clear enhancement in aggregate stability following biochar application, compared to untreated soil, across various sieve diameters. Specifically, aggregate stability values recorded after biochar incorporation were 86.29%, 15.283%, 0.433%, 0.085%, and 0.045% for the respective sieve fractions. In contrast, the corresponding values in the absence of biochar were markedly lower, recorded at 78.85%, 5.01%, 0.12%, 0.07%, and 0%, respectively. This improvement in structural integrity can be attributed to multiple interrelated physical mechanisms. A growing body of experimental and applied research suggests that biochar amendment significantly enhances soil aggregation. This enhancement is primarily due to biochar's highly porous architecture and extensive specific surface area, which promote strong adhesion between fine soil particles such as clay and organic matter. These interactions lead to the formation of larger, more stable aggregates (Lehmann & Joseph, 2015). Moreover, the microporous nature of biochar facilitates improved moisture retention within the soil matrix, thereby mitigating the effects of shrink-swell dynamics that typically contribute to aggregate breakdown. As a result, the structural framework of the soil is better preserved under fluctuating environmental conditions (Mukherjee & Lal, 2013).

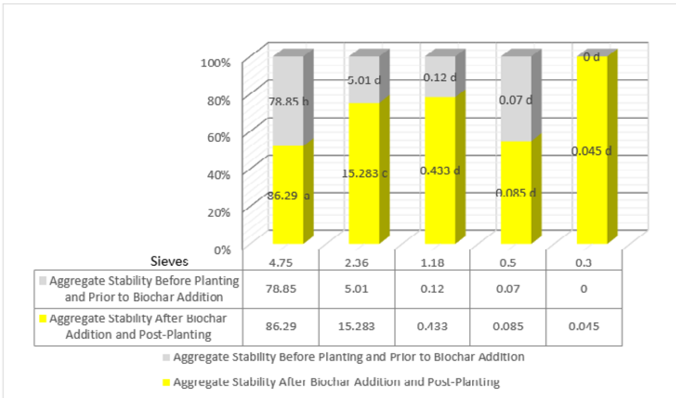

Figure 5. Effect of biochar addition on soil aggregate stability

4.3. Effect of biochar addition on mean weight diameter (mm)

The data presented in Figure 6 indicate that the addition of biochar to the soil resulted in an increase in the mean weight diameter (MWD) of soil aggregates. Specifically, the MWD in untreated soil was recorded at 4.7963 mm, whereas it increased to 5.0125 mm upon the application of biochar at a 0.5% rate. This enhancement can be attributed to the multifaceted physical, chemical, and biological influences of biochar on soil properties, which collectively promote the stabilization and cohesion of fine soil particles into larger, more resistant aggregates. Biochar's highly porous structure and complex surface morphology provide numerous binding sites for fine organic matter, roots, and microbial populations. This structural complexity acts as a catalyst for the aggregation of fine particles, thereby enhancing both the size and stability of soil aggregates (Lehmann & Joseph, 2015). Additionally, biochar contributes to an increase in total soil organic carbon, which further facilitates the formation of bonds among clay, sand, and organic matter particles. These interactions result in the development of more cohesive and structurally stable soil units (Glaser *et al.*, 2002).

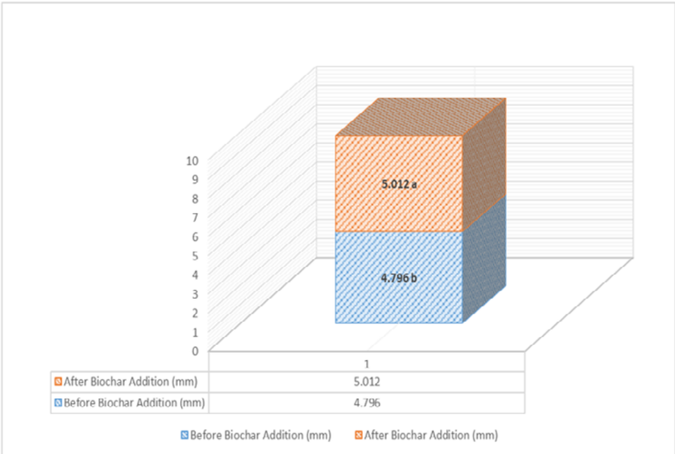

Figure 6. Effect of biochar addition on mean weight diameter

4.4. Leaf chlorophyll content (SPAD):

The data presented in Table 1 reveal no statistically significant differences in chlorophyll content among plants subjected to varying field capacity levels (50%, 75%, and 100%). Similarly, the application of biochar at different rates did not yield significant variation in this trait. However, cultivar effects were evident, with the Rama cultivar exhibiting a significantly higher leaf chlorophyll content (34.833 SPAD) compared to the Nader cultivar (28.566 SPAD). Regarding the interaction between irrigation levels and biochar rates, the combination of 100% field capacity with 0.5% biochar produced the highest chlorophyll content value (35.630 SPAD), significantly surpassing the 50% field capacity treatment without biochar, as well as outperforming the 75% field capacity with biochar treatment. Examining the two-factor interaction between irrigation levels and cultivars, the greatest chlorophyll content was observed under the 100% field capacity combined with the Rama cultivar, reaching 37.133 SPAD. This interaction outperformed all other combinations involving the Nader cultivar across the different irrigation levels. The interaction between biochar levels and cultivars showed that the highest significant chlorophyll content (35.100 SPAD) occurred in the Rama cultivar without biochar addition, outperforming both biochar treatments applied to the Nader cultivar. Conversely, the lowest chlorophyll content was recorded in the Nader cultivar without biochar, measuring 26.422 SPAD. Lastly, the three-way interaction among irrigation levels, biochar rates, and cultivars indicated that the Rama cultivar irrigated at 100% field capacity without biochar attained the highest chlorophyll content value (37.600 SPAD), which was significantly greater than several other treatment combinations. The lowest value (23.967 SPAD) was found in the interaction of 100% field capacity, no biochar, and the Nader cultivar.

Table 1. Effect of irrigation levels, biochar, cultivars, and their interactions on leaf chlorophyll content

Biochar levels	Irrigation levels	Cultivars		Irrigation levels X biochar levels	Mean effect of irrigation levels
		Rama	Nader		
50% FC	0%	25.733 Cd	30.333 a-d	28.033 c	30.408 A
	0.5%	1.233 a-d	34.333 ab	32.783 a-c	
75% FC	0%	29.567 b-d	37.367 ab	33.467 ab	31.483 A
	0.5%	26.300 Cd	32.700 a-c	29.500 bc	
100% FC	0%	23.967 D	37.600 a	30.783 a-c	33.207 A
	0.5%	34.593 Ab	36.667 ab	35.630 a	
Irrigation levels x cultivars	50%	28.483 B	32.333 ab	Mean effect of biochar	
	75%	27.933 B	35.033 ab		
	100%	29.280 B	37.133 ab		
Biochar levels x cultivars	0 %	26.422 C	35.100 a	30.761 A	
	0.5%	30.709 B	4.567 a	32.638 A	
Mean effect of cultivars		28.566 B	34.833 a		

**Means that share the same letters for each factor and interaction are not significantly different from each other according to Duncan's multiple range test at the 0.05 probability level.*

4.5. Plant height (cm plant^{-1})

The data presented in Table 2 indicate that neither irrigation levels nor the average biochar levels exhibited statistically significant differences in plant height. However, plants of the Rama cultivar showed a significant superiority over the Nader cultivar in this trait, with average heights of 35.4723 cm and 34.4722 cm per plant, respectively. No significant differences were observed in the two-way interaction between irrigation levels and biochar rates. Similarly, the two-way interaction between irrigation levels and cultivars reflected the same pattern observed for the individual factors. The two-way interaction between biochar levels and cultivars revealed that the highest plant height (35.5222 cm) was attained by the Rama cultivar without biochar application, showing significant superiority over the corresponding biochar-treated Nader cultivar treatments. Regarding the three-way interaction among irrigation levels, biochar rates, and cultivars, the results in Table 2 indicate no significant differences among the treatment combinations for this trait

Table 2. Effect of irrigation levels, biochar, cultivars, and their interactions on plant height

Biochar Levels	Irrigation levels	Cultivars		Irrigation levels x Biochar levels	Mean effect of irrigation levels
		Rama	Nader		
50% FC	0%	33.433 A	34.767 a	4.1000 a	34.4833 A
	0.5%	34.467 A	35.267 a	34.8667 a	
75% FC	0%	35.700 A	36.067 a	35.8833 a	35.2083 A
	0.5%	33.700 A	35.367 a	34.5333 a	
100% FC	0%	34.533 A	35.733 a	35.1333 a	35.2250 A
	0.5%	35.000 A	35.633 a	35.3167 a	
Irrigation levels x cultivars	50%	33.9500 A	35.0167 a	Mean Effect of Biochar	
	75%	34.7000 A	35.7167 a		
	100%	34.7667 A	35.6833 a		
Biochar levels X Cultivars	0 %	34.5556 B	35.5222 a	35.0389 a	
	0.5%	34.3889 B	35.4222 a	34.9056 A	
Mean effect of cultivars		34.4722 B	35.4723 a		

**Means that share the same letters for each factor and interaction are not significantly different from each other according to Duncan's multiple range test at the 0.05 probability level*

Percentage of Dry Matter in Leaves: The data presented in Table 3 indicate that there were no statistically significant differences among irrigation levels, biochar rates, and cultivars regarding the percentage of dry matter in leaves. Furthermore, no significant differences were observed across all two-way and three-way interaction treatments for this trait.

Table 3. Effect of irrigation levels, biochar, cultivars, and their interactions on percentage of dry matter in leaves

Biochar levels	Irrigation levels	Cultivars		Irrigation levels x biochar levels	Mean effect of irrigation levels
		Rama	Nader		
50% FC	0%	6.1767 A	6.0467 a	6.1117 a	6.1717 a
	0.5%	6.3933 A	6.0700 a	6.2317 a	
75% FC	0%	6.1500 A	6.1400 a	6.1450 a	6.1933 a
	0.5%	6.1733 A	6.3100 a	6.2417 a	
100% FC	0%	6.0933 A	5.9667 a	6.0300 a	6.0175 a
	0.5%	5.9100 A	6.100 a	6.0050 a	
Irrigation levels X cultivars	50%	6.2850 A	6.0583 a	Mean effect of biochar	
	75%	6.1617 A	6.2250 a		
	100%	6.0017 A	6.0333 a		

Biochar levels x cultivars	0 %	6.1400 A	6.0511 a	6.0956 a
	0.5%	6.1589 A	6.1600 a	6.1594 A
Mean effect of cultivars		6.1494 A		6.1056 a

**Means that share the same letters for each factor and interaction are not significantly different from each other according to Duncan's multiple range test at the 0.05 probability level.*

The results presented in Tables (1, 2, 3) regarding growth traits indicate that irrigation levels at 75% and 100% of field capacity produced positive increases compared to the 50% irrigation level. This improvement can be attributed to the sufficient water availability at these higher levels, which enhances the physiological activities of the plant, including photosynthetic efficiency, nutrient translocation, and the synthesis of proteins and sugars, thereby positively affecting growth. Maintaining soil moisture near field capacity ensures the continuity of vital physiological processes such as cell division and elongation, while reducing water stress that can cause stomatal closure and decline in photosynthetic efficiency. Conversely, irrigation at 50% field capacity induces water stress in plants, limiting vegetative growth and reducing biomass accumulation, negatively impacting leaf size, number, in lettuce plants. Farooq *et al.* (2009) emphasized that water stress slows down physiological processes, diminishes nutrient uptake, and triggers the accumulation of stress compounds like abscisic acid (ABA), which contribute to stomatal closure and reduced carbon dioxide absorption, consequently lowering photosynthetic output. Similarly, Karam *et al.* (2006) demonstrated that increased water use efficiency under higher irrigation levels is reflected in enhanced plant growth and yield. Therefore, managing irrigation between 75% and 100% of field capacity is critical for ensuring high productivity in lettuce, a crop sensitive to water stress and requiring a precise balance between water availability and avoidance of saturation.
Furthermore, the findings in Tables (1) and (2) demonstrate that the Rama cultivar significantly outperformed the Nader cultivar in leaf chlorophyll content and plant height. This superiority can be attributed to genetic factors; there may be inherent genetic differences between cultivars that influence growth and development, leading to one cultivar's dominance over the other (Kumar *et al.*, 2000). Alternatively, the genetic composition of one cultivar may be better adapted to its native environmental conditions, granting it a competitive advantage (Lambers *et al.*, 2008). Environmental factors may also play a role, as one cultivar might exhibit greater responsiveness and adaptability to optimal environmental parameters such as temperature, humidity, and light intensity, resulting in its superior performance (Taiz *et al.*, 2015).

5. CONCLUSION

The comprehensive field investigation into the interactive effects of irrigation levels, biochar soil amendment, and cultivar selection on lettuce (*Lactuca sativa* L.) provided clear evidence that strategic water management and soil enhancement practices can substantially improve both soil physical quality and crop growth performance. The application of biochar at 0.5% (w/w) was instrumental in ameliorating key soil physical properties, including increased liquid and plastic limits, improved mean weight diameter (MWD), and greater aggregate stability—attributes that collectively contribute to the resilience and productive capacity of the soil.
Irrigation at 75% and 100% of field capacity proved optimal for maximizing physiological and vegetative responses of lettuce, as evidenced by higher chlorophyll content, greater dry matter accumulation, and improved overall plant vigor when compared to the more restrictive 50% irrigation regime. These findings underline the importance of maintaining an adequate soil moisture regime, especially in arid and semi-arid agroecosystems where water availability and use efficiency are paramount.
Moreover, significant genotypic variation was observed among the studied cultivars, with Rama consistently outperforming Nader across key growth parameters, most notably in chlorophyll concentration and plant stature. This suggests that cultivar choice plays a critical role in mediating plant response to both soil amendment and irrigation management strategies.
In summary, this study underscores that integrated management practices—namely the judicious combination of moderate to full irrigation, biochar amendment, and selection of high-performing cultivars—can synergistically enhance soil health and crop productivity in lettuce cultivation systems. These results hold promise for sustainable intensification efforts and resource use optimization in the eco-touristic forest zone and similar agroecological contexts. Future research should explore the long-term implications of such integrated practices on soil microbial activity, nutrient dynamics, and multi-seasonal crop performance to further consolidate sustainable lettuce production recommendations.

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