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Genotypic Variation and Physiological Compensation of Barley Yield Components under Varying Biochar Application Rates.

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Abstract

This experiment was conducted to evaluate the responses of two barley (*Hordeum vulgare* L.) cultivars, Ibaa 99 and Ibaa 265, to increasing levels of biochar application (0, 2, 4, and 6 ha-1) and determine subsequent effects on some yield components, total productivity, and harvest index. Most of the studied traits exhibited highly significant positive responses as indicated by the data. The highest overall mean values for grains per spike (48.5), 1000-grain weight (44.5 g), total grain yield (4.47 ha-1), biological yield (11.54 ha-1), and harvest index (38.48%) were recorded at the maximum biochar level (6 ha-1), which translated into a 50.5% increase above the control as far as grain productivity was concerned. On the other hand, spike number {m-2} showed a clear parabolic trend, reaching its maximum at 4 ha-1 with 322.5 spikes m-2 and then reduced sharply to 296 spikes m-2 at 6 ha-1 due to a temporary biological nitrogen immobilization. Because of its better genetic and physiological efficiency in source-to-sink partitioning, "Ibaa 99" consistently outperformed "Ibaa 265" in all the parameters studied to give a superior grain output of 3.94 ha-1 and a harvest index of 38.62%. The two-way interaction exhibited strong genotypic sensitivity; "Ibaa 265" suddenly dropped at 6 ha-1,231 m-2, but "Ibaa 99" continued to make an upward linear response for spikes m-2 up to the maximum biochar level (361 spikes m-2). However, "Ibaa 265" exhibited a great biological mechanism for compensating for yield components, maximizing grains per spike to counteract the decrease in spike density (47.0). At 4.82 ha-1 and 12.19 ha-1, respectively, the combination of (Ibaa 99 + 6 ha-1} biochar produced the experiment’s highest grain and biological yields. Thus, it is highly recommended to combine charcoal amendments with high-performing genotypes as a sustainable strategy to maximize barley output.

Keywords: Biochar, Barley, Harvest index, Yield compensation.

Introduction

Barley (*Hordeum vulgare* L.) Barley is viewed as one of the most strategic cereal crops globally, taking the fourth position regarding production volume and agricultural significance; it comes after wheat, rice, and maize only. This is because barley ensures food security for humans and animals and is also fundamental for the malting industry. However, barley production is currently seriously constrained due to the effects of climate change and the progressive degradation of soil fertility, combined with increasing anthropogenic and environmental stress (drought, salinity) that threaten the sustainability of its yield. To address these limitations in agriculture, modern agronomic research has shifted its focus on integrating sustainable, ecologically viable management practices that can foster the revitalization of soil fertility while optimizing water and nutrient use efficiencies.

This is where biochar comes in as a highly effective, sustainable long-term soil carbon sequestration practice that also supports agricultural sustainability and climate change mitigation. The authors define biochar operationally as a carbonaceous stable solid obtained from the thermochemical conversion of organic material at elevated temperatures in the absence of oxygen. This material has specific physicochemical properties that are highly desirable: very large surface area, high degree of porosity, and significant cation exchange capacity. These properties enhance soil structural characteristics by increasing nutrient and water holding capacity while providing an ideal environment for beneficial soil microorganisms in terms of proliferation and metabolic activity.

While a large body of literature has confirmed that biochar amendments stimulate crop ontogeny and yield parameters, plant responsiveness fluctuates. These fluctuations are mainly determined by application rates, soil textural classes, and, most importantly, the underlying genetic variation (genotype) among crop cultivars regarding their nutrient uptake capacity and utilization efficiency of soil amendments (Jeffery et al., 2017). The explicit interaction between biochar application rates and cultivar genotypes is still a major knowledge gap in many agricultural eco-zones because, as recently found (Oram et al., 2020), certain varieties show much better genetic plasticity and root responsiveness to the same soil amendments than do others.

This study was initiated to fill the existing research gap by determining how different biochar application rates affect the vegetative growth and yield components of two barley cultivars. The specific objective was to determine the optimal biochar application rate for maximum sustainable yield, economic return, and climate adaptability under the prevailing environmental conditions of the study area. Recent studies have described biochar as a dual soil conditioner; Al-Wabel et al. (2018) described it as improving soil physical properties by reducing bulk density and increasing aggregate stability and plant-available water in coarse sandy soil. Its high CEC value acts as a nutrient safety net; according to Agegnehu et al. (2017), the loss of leaching of essential macro-nutrients such as nitrogen and phosphorus is reduced by biochar application, by slowly releasing them into the soil solution, thus optimizing synthetic fertilizer efficiency and creating a very favorable rhizosphere for microbial community.

The effect of biochar on crop productivity depends greatly on the dosage of biochar. A recent comprehensive meta-analysis by Jeffery et al. (2017) supported this claim, showing that while moderate amendment rates (e.g., ton10–20 ton/ ha-1) significantly stimulate plant growth and maximize grain yield, high dosages can have negative effects, such as nutrient immobilization or the soil pH moving outside the physiological optimum for the crop. El-Naggar et al. (2019) found that in cereal systems, the most appropriate levels of biochar improve net photosynthetic rates, development of strong root architecture, and high harvest index with grain quality improvement.

Barley also has low genetic diversity which controls its morpho-physiological adaptation to the soil management practices. Oram et al. (2020) verified that different cultivars have varied architecture of the root system and profiles of exudation, which then results in their ability to use the improved rhizosphere given by biochar. For example, Ali et al. (2021) proved that some stress-tolerant genotypes of barley expressed a more positive synergistic response to biochar amendments compared to high yield standard varieties, thus strongly necessitating the evaluation of the genotype-by-environment interaction with respect to biochar levels.

In cereals, substantial genotypic differences have been reported for yield components. For example, Mhamed and Al-Baldawi (2014) in their comparative study on five Iraqi soft wheat (Triticum aestivum L.) cultivars, namely Iraq, Ibaa 99, Ibaa 95, Fatih, and Tahadi found significant superiority in the last cultivar 'Tahadi', which had the highest spike densities of 329.90 and 332.00 m-2 over dimensions of the study. Similarly, Hessan and Moftha (2012) reported substantial varietal differences in spike densities where the local Libyan barley cultivar 'Wadi El-oof' was superior with a mean of 135.60 m-2, whilst 'Giza 123' had the least density of 119.50 m-2. In another study of ten barley genotypes in Ethiopia, Mekonnon (2014) found 'Biftu' to be significantly better than the rest in grain set per spike. In the same vein, Abdul-Jabbar and Nouri (2013) working on two barley varieties, found the local cultivar to be significantly better than the exotic one with a mean 1000-grain weight of 37.48g. These results are in agreement with those of Gill et al. (2017) who assessed three barley cultivars and established that the genotype 'RD 2715' showed significant agronomic superiority by giving the highest mean of 1000-grain weight of 42.1 g..

Materials and Methods

1. Experimental Site and Environmental Conditions

A field experiment was conducted at the Agricultural Extension Research Station in Al-Muthanna Governorate, Iraq during the winter cropping season of 2025-2026. The station is located at latitude 31 and longitude 45.28 E. The macro-climate of the region is semi-arid. Mean ambient temperature during the growing window is 38 C. Composite soil samples were collected randomly from the upper rhizosphere profile at a depth of 0-30 cm prior to the initiation of tillage operations. The soil samples collected were air-dried thoroughly, crushed, and passed through a 2 mm mesh sieve. Physicochemical attributes in the baseline of the experimental matrix were determined after the table compilation. (1).

2. Biochar Production and Characterization

The biochar used in this study was obtained from [plant residues / agricultural waste] by slow pyrolysis at a thermal temperature of 450C for a residence time of [two hours] under oxygen-limited (anoxic) conditions. After the thermochemical conversion, the resulting biochar was ground using a mechanical grinder and then sieved to pass a 2mm mesh to ensure uniformity of structure. The basic physicochemical properties of the biochar matrix, including pH, electrical conductivity (EC), specific surface area, and total elemental nitrogen {N}, phosphorus {P}, and potassium K concentrations, were determined quantitatively in conformity with standard analytical methods

3. Experimental Design and Treatments

A field experiment was conducted in a Randomized Complete Block Design (RCBD) with a split-plot arrangement and three replications. Barley cultivars, 'Ibaa 99' and 'Ibaa 265' representing two different genotypes, were randomly assigned to the main plots. Biochar application rates were assigned to the sub-plots in four specific treatment levels: B0 (control,0 ton/ ha-1), B1 (low rate, 2 ton/ ha-1), B2 (medium rate, 4 ton/ ha-1), and B3 (high rate, 6ton/ ha-1). Biochar treatments were applied through complete mixing and incorporation into the upper 15cm soil layer two weeks before the scheduled sowing date to attain physical equilibrium for stable biochemical interactions within the soil matrix.

4. Experimental Factors

1. Biochar Factor:

Based on soil volume, four levels of biochar were administered: 0%, 2.5%, 3.5%, and 4.5%, which were given the names B0, B1, B2, and B3, respectively. By multiplying the three dimensions (Length × Width × Depth: 200 cm 30cm), the soil volume for each experimental unit was calculated to be 1,200,000 cm^3. The required biochar amounts were determined as follows using these percentages:

- 1,200,000 x 0.02.5 = 30.000 cm for the 2.5% level (B1)
- For the 3.5% level (B2): 1,200,000 x 0.035 = 420000 cm.
- For the 4.5% level (B3): 1,200,000 x 0.045 = 54000 cm

For each individual experimental unit, these amounts were well mixed into the soil. The first level (B0) acted as a control, and no biochar was added.

2.Factor A: Barley Cultivars (Main Plots)

This factor evaluated two strategic genotypes of barley (*Hordeum vulgare* L.), which were assigned the statistical codes **V1** and **V2** respectively:

1. **V1**: 'Ibaa 99' cultivar.
2. **V2**: 'Ibaa 265' cultivar.

3. Sowing and Crop Management

On November 1st, the seeds were sown for the 2023 and 2024 seasons at a seeding density of 120 kg/ha (Ministry of Agriculture, 2012). Basic fertilization was done after that.

- Nitrogen (N): A dose of 120 kg N ha-1 was applied in the form of urea, which contains 46% nitrogen. The entire dose was split into four equal parts. The first part was applied at the time of germination, the second at the stage of elongation, the third at booting, and the last one at full flowering.

- Phosphorus (P): 80 kg ha-1 of Triple Superphosphate, with 46% P2O5, was applied once during soil preparation (Mohammed, 2017). • Potassium (K): It was applied according to the levels of treatments planned in two phases-first before sowing and the second during the early stage of germination (Kommineni, 2024). The first season's harvest was completed on May 15, 2024.

5. Investigated Agronomic and Yield Traits

1. Number of Fertile Spikes m^{-2}

The numerical density of fertile spikes was determined at the physiological physiological maturity stage. Spikes were systematically counted from all harvested plants within the two central rows of each experimental unit (plot), and the data was subsequently calibrated and expressed per square meter.

2. Number of Grains per grains

This parameter was determined by randomly selecting ten representative spikes from each experimental plot. These spikes were manually threshed, the grains were continuously counted, and the dynamic average was recorded as the number of grains per spike.

3. 1000-Grain Weight (g)

A representative sub-sample of 1000 grains was randomly isolated from the net grain yield of each experimental unit. The isolated grains were subsequently weighed using a high-precision electronic analytical balance, and the weight was recorded in grams.

4. Grain Yield ton/ ha^{-1}

Grain yield was estimated from the total plant biomass harvested within the two central rows of each plot to eliminate border effects. Following manual threshing and the meticulous separation of straw from the grains, the clean grain mass was weighed. The collected weight data was then mathematically extrapolated and converted from grams per plot to tons per hectare ton/ ha-1.

5. Biological Yield ton/ ha^{-1}

The biological yield (total dynamic biomass) was determined by weighing the entire harvested plant material (straw + grains) from the two central rows of each experimental unit after ensuring complete air-drying. The recorded biomass data was subsequently transformed from grams per square meter g m-2 to tons per hectare ton/ ha^{-1}.

6. Harvest Index (%)

The harvest index (HI) was dynamically calculated for each experimental treatment according to the structural relationship between economic yield and total biological allocation, as defined by Donald (1962), utilizing the following equation:

{Harvest Index (%) = Grain Yield ha-1/ Biological Yield ha-1X100

6. Statistical Analysis

The empirical data collected for the investigated vegetative growth attributes and yield components were subjected to a rigorous analysis of variance (ANOVA) according to the split-plot design hierarchy, utilizing the **Genstat** statistical software package (v.18 or modern equivalent). Treatment means were statistically compared and separated using the **Least Significant Difference (LSD)** test computed at a strict probability threshold of $P \le 0.05$. All statistical procedures, mathematical partitions, and variance assessments were executed in compliance with the biometrical methodologies established by Al-Rawi and Khalaf Allah (1980)

Results and Discussion

1. Number of Fertile Spikes per Square Meter m^2)

Data from the study showed a curvilinear increase in the numerical density of barley spikes wide open to biochar application from 0 to 4 t ha−1. The grand mean increased significantly from 271 to 322.5 spikes m−2. However, when the rate of amendment was increased to 6 t ha−1, the overall mean significantly dropped to 296 spikes m−2. In this case, therefore, the dimensional changes were highly significant since the least significant difference (LSD0.05) was 15.2.

The initial increase up to the 4 t ha−1 baseline can be primarily explained by the multi-functional edaphic improvements that biochar usually induces. These are remediation to physical mechanics of soil, optimization of hydraulics in the rhizosphere, and increased chemical availability of essential macro and micronutrients, which together stimulated effective tillering and enhanced crown bud differentiation.

On the other hand, the unproductive repression in spike density observed at the highest rate of application (6 t ha−1) can be explained scientifically through the complicated ecological concept of temporary biological nitrogen immobilization. Incorporating huge, focused amounts of biochar a substrate inherently distinguished by an extremely wide carbon-to-nitrogen (C/N) ratio triggers an immediate carbon flash in the rhizosphere. This input encourages heterotrophic soil microbial populations to thrive exponentially, compelling them to scavenge and immobilize the easily accessible inorganic pool of soil nitrogen (NO3− and NH4+) for synthesizing their own cellular biomass. This nutrient hoarding induced by microbes thus creates a short-term, acute nitrogen deficiency exactly at the nitrogen-sensitive vegetative tillering stage, which results in the constriction of vasculature and a high mortality of young tillers, indirectly reflected as a decrease in final spike density.

The main effect analysis also confirmed a clear significant physiological superiority for the cultivar 'Ibaa 99', which recorded the highest mean spike density (321.5 spikes m−2) over 'Ibaa 265', which had an average output of 271.25 spikes m−2. Deep-seated genetic differences and differential gene expression controlling hormonal balance between the two genotypes are the major factors responsible for this phenotypic divergence. The cultivar 'Ibaa 99' is, therefore, assumed to possess a more efficient physiological mechanism for active tiller initiation, with a high rate of survival of initiated tillers throughout the period up to the heading stage, while that of 'Ibaa 265' is assumed to have an alternative strategy in carbon allocation where its genetic architecture gives priority to the distribution of net photosynthates towards late yield formation; such as single grain volume or expansion of spike longitudinal axis at structural cost by keeping the vegetative canopy dense.

The two-way interaction (Cultivar×Biochar) revealed an interesting and highly significant genotypic difference. The cultivar 'Ibaa 99' showed sustained genetic plasticity, continuously and positively linearly responding up to the highest biochar concentration, where it recorded a peak density of 361 spikes m−2. In contrast, 'Ibaa 265' collapsed abruptly and severely at 6 t ha−1, falling to 231 spikes m−2 after climbing to 312 spikes m−2 under the 4 t ha−1 treatment matrix. This sharp divergence in behavior strongly supports the existence of acute genotypic sensitivity to high chemical thresholds of biochar in the soil rhizosphere; some cultivars can, therefore, either tolerate or take advantage of heavy bio-enforcement, while for others it represents a severe physiological bottleneck..

Table (2): Effect of different biochar application rates, cultivars, and their interaction on the number of fertile spikes per square meter m^{-2}

Biochar Levels	V1	V2	Biochar Means
0	281	261	271
2	311	281	296
4	333	312	322.5
6	361	231	396
Means	321.5	271.25	
L.S.D$_{0.05}$	V	B	**Interaction**
	12.4	15.2	21.5

2.Number of Grains per Spike grains spike-1

Results of the study showed a statistically significant increase in the average number of grains per spike with the increase in rates of biochar application. The grand mean progressed from 39.0 grains spike-1 in the control treatment (0ton/ ha-1) to its maximum value at the highest application level of 6 ton/ ha-1, recording 48.5 grains spike-1. This gradual improvement shows the optimum condition of nutrition and water for the plant during the most critical ontogenetic stages of spike initiation and anthesis. Biochar balanced and sustained the flow of macro and micronutrients by raising the Cation Exchange Capacity (CEC) of the soil and holding moisture in the rooting zone. This nutritional and physiological stability curtailed floret abortion phenomena in the developing spikes to enhance pollination and fertilization efficiencies and maximize the absolute number of successfully set grains per individual spike.

The cultivar 'Ibaa 99' expressed a significant positive mean performance with 45.5 grains spike-1 compared to 41.5 grains spike-1 for 'Ibaa 265', indicating the superiority of 'Ibaa 99' over the other cultivars. The structural superiority observed in this study was due to genetic variability among the cultivars for sink capacity. The cultivar 'Ibaa 99' was genetically more plastic in increasing the length of the longitudinal axis of the spike rachis to accommodate a higher density of differentiated spikelets. It was also outstanding in metabolic efficiency for translocation of non-structural carbohydrates and mobile photosynthates or assimilates from the source organs (leaves and stems) to the developing reproductive structures (sinks) during the pre-heading critical developmental stage.

The two-way interaction Cultivar {Biochar showed a harmonious positive and ascending response across both genotypes. The treatment combination (‘Ibaa 99’ + 6ton/ ha-1 biochar) achieved the absolute highest value in the matrix, spiking to 50.0 grains spike-1. Simultaneously, ‘Ibaa 265’ responded remarkably well to the highest soil amendment rate, spiking sharply to 47.0 grains spike-1 at the $6\text{ ton/ ha-

1 level from a baseline of 37.0 grains spike-1 in its respective control.

This particular response indicates a very important biological process referred to in crop physiology as yield components compensation. When the higher biochar rate (6 ton/ha induced a temporary nitrogen immobilization that reduced the spike numerical density of 'Ibaa 265' per square meter at the tillering stage, the reduced number of surviving plants per unit area experienced a massive relief from inter-plant competition. This created a "glut" of available growing space, intercepted solar radiation, and localized soil nutrients. The nutrient flush came at just the right time-at the late-season grain formation phase when the biochar matrix had already started releasing steadily earlier adsorbed ions into the soil solution. Therefore, the remaining spikes were able to take advantage of this resource surplus to grow vigorously and compensate effectively for the vegetative numerical shortage by driving a much higher grain set within each individual spike.

Table (3): Effect of different biochar application rates, cultivars, and their interaction on the number of grains per spike (grains spike^{-1})

Biochar Levels	V1	V2	Biochar Means
0	41	37	39
2	43	40	41.5
4	48	42	45.0
6	50	47	48.5
Means	45.5	41.5	
L.S.D$_{0.05}$	V	B	**Interaction**
	2.1	2.8	3.9

3. 1000-Grain Weight (g)

The statistical data show a steady, progressive, and significant increase in the mean 1000-grain weight of barley with applied biochar. The grand mean advanced from 38.25g in the control treatment to a definite maximum of 44.5g under the highest amendment rate of 6ton/ ha-1. This substantial enhancement can be physiologically attributed to the functional role of biochar in extending the grain filling period and optimizing its metabolic efficiency. Biochar is described as acting like a sustainable porous reservoir for moisture and nutrients within the soil matrix; this buffers the plant against nutrient depletion or late-season terminal drought stress at a time when the critical post-anthesis developmental phases (milky and dough stages) are reached.

This stability in water and nutrient supply allows the green leaf area to be maintained and supports canopy photosynthesis, especially that of the flag leaf. This ensures better translocation and remobilization of non-structural carbohydrates and mobile proteins from source organs (vegetative structures) to developing reproductive sinks (grains). Thus, the continuous translocation of assimilates from source to sink maximizes net dry matter accumulation within individual caryopses, resulting in plump, well-filled, and heavier grains. The main effect analysis showed a statistically significant superiority for the cultivar 'Ibaa 99' with an overall mean of 42.42g compared to 40.15g for 'Ibaa 265'. This divergence indicates genetic differences in sink capacity and enzymatic velocity of carbohydrate conversion. The cultivar 'Ibaa 99' is assumed to have higher assimilate translocation efficiency and better genetic expression in regulating endosperm cell division and expansion during early grain set. This cellular stretchiness allows its particles to make a larger physical volume, therefore accommodating much higher amounts of starch granules and storage proteins than 'Ibaa 265'.Regarding the two-way interaction Cultivar {Biochar}, the statistical analysis indicated a non-significant (N.S.) effect, showing that the main factors acted independently on this parameter. This statistical behavior is quite logical since grain weight is a trait strictly controlled by strong genetic factors and varietal characteristics, making it less plastic under variable environmental interactions. However, from an arithmetic point of view, the treatment combination of ('Ibaa 99' + 6ton/ ha-1} biochar) recorded the absolute highest numerical value in the data matrix at 46.0gable (4): Effect of different biochar application rates, cultivars, and their interaction on the 1000-grainweight(g)

Table (4): Effect of different biochar application rates, cultivars, and their interaction on 1000-Grain Weight (g)

Biochar Levels	V1	V2	Biochar Means
0	39.5	37.0	38.25
2	41.2	39.5	40.35
4	43.0	41.1	42.05
6	46.0	43.0	44.5
Means	42.42	40.15	
L.S.D$_{0.05}$	V	B	**Interaction**
	1.15	1.62	N.S

4.Grain Yield (ton/ ha^{-1})

The table gives data on the total grain yield of barley per unit area and shows a very strong, positive, and statistically significant improvement. The grand mean for grain yield increased from 2.97 tons per hectare in the control treatment (0 tons per hectare) to 4.47 tons per hectare at the highest application rate of 6 tons per hectare. This corresponds to a very high agronomic increase of 50.5% compared to the non-amended control plots.

The linear trend in improving grain yields reflects the final structural enhancement accruing from biochar, involving energy balance at large, and moisture management and growth kinetics over the entire season of the crop. Biochar did not only change the mechanical and biological properties of the root rhizosphere during the initial stages of plant development but also acted as a slow-release regulator for water and nutrient ions important to the plant. Thus, such sustained support of the soil optimizes the net photosynthetic rate (Pn) while senescence of leaves is postponed, keeping a functionally active green leaf area index (LAI) until the critical grain-filling period after anthesis. Agronomic yield components previously assessed, i.e., grain count per spike and 1000 grain weight, interacted synergistically to enhance total grain yield per hectare. These interactions affirm that soil bio-enforcement through biochar has significant productive and agronomic potential within the examined soil matrix, even at elevated application rates.

The analysis of variance for grain yield showed that the main effect of barley genotypes was highly significant. That's in addition to the fact that 'Ibaa 99' was significantly better than 'Ibaa 265' in grain yield at 3.94 t ha−1 and 3.46 t ha−1, respectively. The superiority of 'Ibaa 99' in grain yield was associated with its superiority in all major yield component structures. As earlier established in this write-up, 'Ibaa 99' had superior physiological capacities for spike numerical density, intra-spike floret fertility (grain count), and single grain mass accumulation. The genetic coherence and balanced yield architecture of 'Ibaa 99' improved its source-to-sink conversion efficiency by better capturing solar radiation and more effectively using available soil inputs in converting them into economic dry matter (grain mass) compared to 'Ibaa 265'.

The Biochar x Cultivar interaction was highly significant for total grain yield. 'Ibaa 99' at 6 ton/ha-1 of biochar had the highest absolute yield over all other treatments at 4.82 ton/ha-1. It is important to note that at this treatment level where there was a structural reduction in spike density due to the early transient immobilization of nitrogen, 'Ibaa 265' was however consistently upward and reached its maximum individual agronomic yield of 4.12 ton/ha-1 at the same biochar application rate of 6 t/ha-1. This trend shows a strong positive compensation from intra-spike yield parameters—specifically grains per spike and grain weight—that sufficiently offset the numerical shortfall in spikes per unit area, resulting in a net positive increase in final grain yield per hectare..

Table (5): Effect of different biochar application rates, cultivars, and their interaction on grain yield ton/ ha^{-1}

Biochar Levels	V1	V2	Biochar Means
0	3.12	2.82	2.97
2	3.63	3.22	3.42
4	4.22	3.71	3.96
6	4.82	4.12	4.47
Means	3.94	3.46	
L.S.D$_{0.05}$	V	B	**Interaction**
	0.18	0.25	0.36

5.

Biological Yield ton/ ha^{-1}

The statistical analysis showed an increase in the average biological yield of barley over the treatments, which was linear and significant. The total above-ground biomass can be defined as the average biological yield. It started from a baseline of 7.91 tons per hectare in the control treatment (0 tons per hectare). It increased with each successive increment of biochar added to the soil to a maximum of 11.54 tons per hectare at 6 tons per hectare.

Biomass continues to accumulate, manifesting the positive effects of biochar on the physical, chemical, and biological properties of the soil under experimentation. Biochar has a very large internal specific surface area with a highly porous structure, thus enhancing the retention of moisture and checking the leaching of important ions of macro- and micronutrients. This provides for an optimized root rhizosphere which ensures a constant and sustainable supply of water and nutrients to the root system at all phenological stages considered critical. The ongoing physiological support thus provided directly stimulates cellular division and elongation within the meristematic tissues, resulting in increased plant height, a higher leaf area index (LAI), and a more rapid rate of dry matter accumulation in the vegetative source organs (stems and leaves), thereby making a significant contribution to final grain deposition as well. This structural response underscores the importance of soil bio-enforcement through biochar in developing a robust, high-capacity vegetative canopy that enhances radiation use efficiency (RUE), allowing the crop to intercept solar radiation more effectively and convert it into total biological mass.

Performance differences were assessed between two cultivars, and the results pointed to a clear and highly significant advantage presented by cultivar 'Ibaa 99', which attained the highest average biological yield of 10.17 ton/ha-1, as opposed to 'Ibaa 265', with an average of 9.27 ton/ha-1. This difference can mainly be ascribed to the genetic differences between the two genotypes and their vegetative growth characteristics. 'Ibaa 99' has genetically superior genes which are expressed differentially, enabling it to form a more dense and strong vegetative framework. This framework has thicker stems than 'Ibaa 265', offering very substantial resistance to lodging; broader leaf blades; and higher chlorophyll density per unit of leaf area. All these features give 'Ibaa 99' a superior net assimilation rate (NAR) as well as enhanced physiological capacity for total biomass accumulation in its tissues throughout the ontogenetic cycle, surpassing that of 'Ibaa 265'.

The total biomass was significantly influenced by the two-way interaction of Cultivar and Biochar. The combination of treatment involving 'Ibaa 99' with 6 ton/ha-1 of biochar achieved the highest biological yield throughout the trial, reaching 12.19 ton/ha-1. 'Ibaa 265' showed a consistent and pronounced upward trend in its individual biomass performance and reached its maximum at the 6 ton/ha-1 level with 10.89 ton/ha-1, in contrast to a baseline yield of 7.61 ton/ha-1 in the corresponding control plot. These results show that both genotypes exhibited high levels of biological responsiveness to biochar addition, despite their genetic differences in structural canopy architecture.

Table (6): Effect of different biochar application rates, cultivars, and their interaction on biological yield t ha-1)

Biochar Levels	V1	V2	Biochar Means
0	8.21	7.61	8.21
2	9.49	8.69	9.49
4	10.81	9.91	10.81
6	12.19	10.89	12.19
Means	10.17	9.27	10.17
L.S.D$_{0.05}$	V	B	**Interaction**

	0.45	0.62	0.88

6.

Harvest Index (%)

Empirical data shows a stepwise and statistically significant increase in the average harvest index (HI) of barley with the increase in levels of biochar amendment. The grand mean systematically rose from a baseline of 37.33% in the control treatment (0 ton/ha-1) to a final value of 38.48% under the maximum application rate of 6 ton/ha-1.

This large increase in HI indicates that soil ecological modification with biochar did not simply increase structural vegetative growth (biological yield) but optimized resource translocation by the plant to achieve a well-balanced higher proportion of non-structural carbohydrates toward reproductive sinks (spikes and developing grains). Hydric and nutritional continuity within the barley root zone during late developmental stages (from anthesis to grain filling) was a prerequisite for biochar to enhance efficiency in translocation and remobilization. Therefore, net growth and accumulation rate of economic grain yield surpassed or moved in harmony with total biomass growth velocity to raise overall harvest index value.

The main effect analysis revealed that statistically 'Ibaa 99' was significantly better than all other treatments with an overall average harvest index of 38.62%, while 'Ibaa 265' had an average of 37.28%. This variance is related to the morpho-physiological and genetic differences between the two genotypes in terms of behavior on dry matter partitioning and allocation. Apparently, 'Ibaa 99' has a more flexible physiological and genetic mobilization and vascular remobilization of stored pre-anthesis stem reserves. It further mobilizes these mobile carbohydrates specifically to the grains during the period of grain filling. This makes it a highly efficient cultivar regarding economic translocation efficiency as compared to 'Ibaa 265', which genetically had a tendency to retain a higher fraction of dry matter locked within its structural vegetative framework (straw and vegetative stover).

The interaction effect between {Cultivar Biochar} was non-significant (N.S.) on the harvest index, showing that the extra benefits of biochar rates were similar in both cultivars without any special genotypic divergence in the relationship. However, the highest total performance was observed under the treatment combination of ('Ibaa 99' + 6ton/ ha-1 biochar) with a value of 39.35% in absolute terms.

Table (7): Effect of different biochar application rates, cultivars, and their interaction on harvest index (%)

Biochar Levels	V1	V2	Biochar Means
0	37.81%	36.85%	37.81%
2	38.43%	36.79%	38.43%
4	38.90%	37.89%	38.90%
6	39.35%	37.62%	39.35%
Means	38.62%	37.28%	38.62%
L.S.D$_{0.05}$	V	B	**Interaction**
	0.65%	0.92%	N.S

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