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# Effect of Integrated Nutrient Management on Lentil (*Lens culinaris* L.) Productivity and Soil Health

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## ABSTRACT

The effects of integrated nutrient management (INM) on the growth, yield, and soil health of two lentil varieties (Dasht-21, Black Lentil Panjgur) were studied at the Research Farm Directorate of Oilseed Crop, Agriculture Research Institute (ARI) Quetta, Pakistan, from the 2023–2024 Rabi season. A total of seven treatments were studied and assigned at random in a complete block design, control (T1), compost (T2), full NPK (T3), biochar (T4), half biochar + half NPK (T5), half compost + half NPK (T6), and half compost + half biochar + half NPK (T7). Dasht-21 variety lentils produced a greater height, shoot biomass, pods per plant, and greater 1000-grain and grain yield (554 kg ha-1) than Black Lentil Panjgur (499 kg ha-1). Among the treatments, T7 produced the highest grain yield (701 kg ha-1) and harvest index. Other treatments, T5 and T6 maximized pods per plant and biological yield, respectively, and showed greater than control in most growth and yield parameters. Soil analysis after harvest showed T7 and T6 produced greater organic treatments than control and lead to greater improvement (especially in the subsurface) than other treatments in microbial biomass, Soil organic carbon (SOC), and nutrient availability. MBC, MBN, and SOC.Yield components showed strong positive correlations such as grain yield with biological yield (r = 0.83; pods per plant, r = 0.78). These were driven mostly by above ground traits along PC1, while root traits characterized PC2. The combination of compost, biochar, and reduced NPK (T7) markedly increased lentil productivity and soil amelioration, exhibiting efficacy as an environmentally sustainable alternative in semi-arid, alkaline, and variable soils.

## 1. INTRODUCTION

The lentil (*Lens culinaris* L.) is a significant legume crop around the globe, due to its high protein content (20-30%) and its ability to fix nitrogen, enhancing soil quality in sustainable agricultural systems.In Pakistan, lentils are mainly grown in the Punjab and Balochistan regions, but soil quality, water scarcity, and nutrient imbalance have resulted in suboptimal yields of approximately 570 kg ha$^{-1}$ (Kumar et al., 2023). Balochistan highland regions, particularly in and around Quetta, have a suitable cool climate for lentil production, and winter planting during the 200-300 mm annual rain is positively correlated with lentil production.however, soil alkalinity and poor soil organic matter remain impediments to optimal lentil growth (Dahal et al., 2024).

Integrated Nutrient Management (INM) combines both organic and inorganic nutrients to improve nutrient availability and soil structure, while minimizing the use of harmful chemical fertilizers. INM has been shown to improve the productivity of legumes by enhancing root nodule formation and the overall nutrient uptake (Kumar et al., 2022(Tawab et al., 2024). For instance, the combination of the application of livestock manure and synthetic fertilizers has been found to reduce soil bulk density and increase soil microbial activity (Bhattacharya et al., 2023). Compost and biochar (carbon-rich soil amendment produced from pyrolysis) has been shown to improve soil nutrient and moisture retention (Sahu et al., 2017). Compost also provides organic matter which stimulates biological activity within the soil. These soil amendments increase the yield of legume crops by 10 to 20 percent by enhancing root development and nitrogen fixation (Singh et al., 2017).

Locally grown crops in Quetta, such as Dasht-21, which has been adapted to grow in drought conditions, and the Black Lentil Panjgur, which is known to be resistant to disease, have been documented. However, there is little research on the effects of INM in these specific genotypes under Balochistan conditions. This study evaluate the impact of INM on growth, yield, and soil attributes, and employed multivariate methods, particularly PCA and correlation, to assess the structure of the relationships of principal components. The author posited that integrated INM amendments would be more effective than other single amendments in boosting productivity and improving soil health.

## 2. MATERIALS AND METHODS

### 2.1: Experimental Site and Design

The experiment was conducted at the Agriculture Research Institute (ARI) Sariab Road, Quetta, Pakistan (30°11'N, 67°00'E; elevation 1680 m), during the Rabi season of 2023-2024. The site's soil is sandy clay loam, with initial pH 0-15 and 15-30 (7.89, 7.72), organic carbon (0.54%,0.57%) available N 0.027%, 0.028%, P 3.88, 3.70 mg kg$^{-1}$, and K 116, 109 mgkg$^{-1}$(Table 2.1).

A randomized complete block design (RCBD) with 3 replications was used. Two lentil varieties (Dasht-21 and Black Lentil Panjgur) were tested under seven treatments in plots of 6 m$^2$ (3 m × 2 m), with row spacing 30 cm and plant spacing 10 cm. Seeds were sown at 20kg ha$^{-1}$ in November 2023. Detailed initial soil physio-chemical and biological properties are presented in (Table 2.1).

**Table 2.1**

*Initial physico-chemical and biological properties of the experimental soil at Agriculture Research Institute, Quetta*

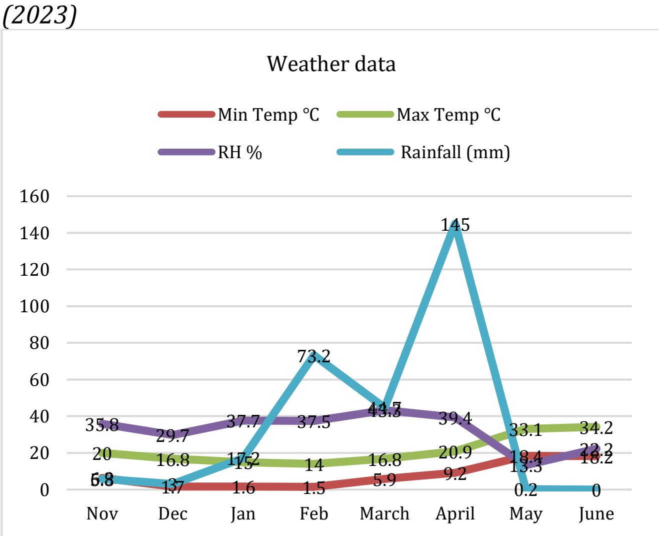
| Parameters | Units | Results | | Method | Reference |
|---|---|---|---|---|---|
| | | 0-15 (cm) | 15-30(cm) | | |
| Texture class | | Sandy Clay loam | Sandy Clay loam | International pipette method | Piper (1966) |
| Ph | | 7.89 | 7.72 | Glass electrode pH meter | Jackson (1962) |
| Electrical Conductivity (EC) | dSm$^{-1}$ | 0.54 | 0.56 | Conductivity meter in 1:2 soil:water extract | Richards (1954) |
| Organic matter | (%) | 0.54 | 0.57 | SOC × 1.724 | Nelson and Sommers (1996) |
| Total nitrogen | (%) | 0.027 | 0.028 | Alkaline permanganate method | Subbiah and Asija (1956) |
| Available phosphorous | mg kg$^{-1}$ | 3.88 | 3.70 | Olsen's 0.5 M $NaHCO_3$ extractable P (pH 8.5), ascorbic acid colorimetry | Olsen et al. (1954) |
| Available potassium | mg kg$^{-1}$ | 116 | 109 | 1 N ammonium acetate extractable K, flame photometry | Hanway and Heidel (1952) |
| Microbial biomass carbon (MBC) | mg C kg$^{-1}$ | 67 | 69 | Chloroform fumigation–extraction method | Vance et al. (1987) |
| Microbial biomass nitrogen (MBN) | mg N kg$^{-1}$ | 60 | 62 | Chloroform fumigation–extraction method | Brookes et al. (1985) |
| Soil organic carbon (SOC) | G C kg$^{-1}$ | 0.50 | 0.51 | Walkley–Black rapid titration method | Walkley and Black (1934) |

### 2.2: Weather Data

The weather data recorded from the Agriculture Research Institute weather station and the maximum temperature was observed in the month of May (33.1°C) and minimum was observed in the month of February (1.5°C), the highest rainfall (145 mm) occurred in April ,while may received the least (0.2mm). The Detailed of weather data of experimental site are present in (figure 2.1).

**Figure 2.1**

*Average means monthly weather data of experimental location for the crop growth season from November to June (2023)*




**Treatments**

T$_1$: Control (no amendments)
T$_2$: Compost (5 t ha$^{-1}$)
T$_3$: NPK (20:50:30 kg ha$^{-1}$)
T$_4$: Biochar (5 t ha$^{-1}$)
T$_5$: Half biochar (2.5 t ha$^{-1}$) + half NPK (10:25:15 kg ha$^{-1}$)
T$_6$: Half compost (2.5 t ha$^{-1}$) + half NPK (10:25:15 kg ha$^{-1}$)
T$_7$: Half compost (2.5 t ha$^{-1}$) + half biochar (2.5 t ha$^{-1}$) + half NPK (10:25:15 kg ha$^{-1}$)

### 2.3: Data Collection

The number of plants per square meter was calculated by counting plants in one-meter row length and converting to m$^2$. The number of branches per plant was determined by averaging five randomly selected plants per plot. For nodules per plant, five intact-root plants were carefully uprooted, washed, and nodules were counted after detachment. Root length was measured from five randomly selected plants per plot, using a scale from the base of the stem to the longest root tip. Plant height was recorded using a measuring tape from soil level to the terminal shoot. Root fresh weight was taken by uprooting five plants, gently washing and drying the roots, and then weighing them. Shoot fresh weight was measured by cutting shoots at ground level from five plants and immediately weighing them to avoid moisture loss. For root dry weight, roots were oven-dried at 60–70°C for 48–72 hours and weighed after cooling in a desiccator. Shoot dry weight was determined by drying shoots in an oven under the same conditions until constant weight was achieved. Yield parameters included the number of pods per plant, calculated from five randomly selected plants per plot. The number of seeds per pod was also recorded and averaged. An electronic balance was used to determine the 1000-grain weights of each of the three seed samples drawn at random. Sun-dried biomass harvested from 1 $m^2$ was used to obtain the biological yield which was converted to kg $ha^{-1}$. The seed yield was recorded after threshing and was also converted to kg $ha^{-1}$. Harvest index was calculated as: $HI(\%) = \frac{Grain\ Yield}{Biological\ Yield} \times 100$

Soil physicochemical and biological assessments employed standardized protocols. Soil pH was measured potentiometrically in a 1:1 soil water mix, using a pH meter standardized with buffers at pH 4 and 9 (Peech, 1965). Electrical conductivity (EC) was assessed on the saturated paste using a conductivity meter (Rhoades, 1996). Soil organic carbon (SOC) was assessed via wet oxidation by digesting 2g soil with 1N potassium dichromate and concentrated sulfuric acid, then titrated with 0.5N ferrous sulfate with a diphenylamine indicator (Nelson & Sommers, 1996).

Available phosphorus was extracted by shaking 5g soil with 0.5M sodium bicarbonate ($NaHCO_3$), with the resulting filtrate analyzed colorimetrically at 880 nm after acidification and reaction with ascorbic acid (Kuo, 1996). Available potassium was extracted using the AB-DTPA method and quantified by flame photometry (Soltanpour & Schwab, 1977). Organic matter (OM) was estimated based on SOC, calculated as OM = Walkley-Black C × 1.72, following dichromate digestion and titration (Nelson & Sommers, 1996). Available nitrogen was assessed colorimetrically after digesting 0.2g soil with a selenium-containing mixture at 360°C and diluting the colorless digestate (Bremner, 1965). Microbial biomass carbon (MBC) and nitrogen (MBN) were determined by the chloroform fumigation-extraction method; MBC was calculated as (fumigated extract C - unfumigated extract C) × 2.64 and MBN as (fumigated extract N - unfumigated extract N) × 1.46, with carbon in the 0.5M $K_2SO_4$ extracts measured according to Vance et al. (1987). Soil texture was characterized by the Bouyoucos hydrometer method after dispersing 40g soil overnight in sodium hexametaphosphate solution, with textural class determined using the ISSS triangle (Mwendwa, 2022).

### 2.4: Statistical Analysis

Data were analyzed using ANOVA within Statistix 8.1. Means were compared using the Least Significant Difference (LSD) method at $p<0.05$. Principal Component Analysis (PCA) and Pearson Correlation (PCA) were done in R for the 15 agronomic traits and their respective variabilities and associations. Contributions were visualized using scree plots and biplots.

## 3. RESULTS

### 3.1 Growth Parameters

Statistically significant differences were found between the two varieties of lentil plants for plant height, fresh weight of root, fresh weight of shoot and dry weight of shoot; whereas, the number of plants per square meter, branches per plant, nodules per plant, root length and root dry weight were not found to differ significantly (P>0.05) (Table 3.1). Variety 1 had significantly higher plant height (31.21 cm), shoot fresh weight (30.10 g) and shoot DW (18.38 g) compared to those of Variety 2. In turn, the root fresh weight of Variety-2 was significantly higher (1.04 g) than in Variety 1 (0.96 g). Although not statistically significant, Variety no.2 resulted in slightly higher number of nodules (9.43) and root dry weight (0.60 g). Significant differences (P ≤ 0.05) were found between the INM treatments, in all of the traits measured except root length. The highest values of plant density (38.75 number of plants/m2), branches per plant (14.16 number of branches/plant), and nodules per plant (12.06 nodules/plant) were recorded in the case of treatment $T_6$; it also showed the highest shoot fresh weight (36.95 gr) and a relatively high value of the shoot dry weight (18.82 gr). In contrast, treatment $T_5$ was the best performing showing the tallest plants (32.43 cm) with the highest root dry weight (0.72 g) and high shoot biomass. In comparison, $T_1$ had the lowest all measured parameters of performances of plant density 25.16 $m^{-2}$, number of branches per plant (9.63), number of nodules per plant (5.35), shoot fresh weight (21.32g) and shoot dry weight (12.59g), showed a striking improvement in growth after integrated nutrient application.

**Table 3.1:**
*Effect of INM and varieties on growth parameters*

| Varieties | Number of plants ($m^2$) | Number of branches $plant^{-1}$ | Number of Nodules $plant^{-1}$ | Root length (cm) | Plants height (cm) | Root Fresh Weight (g) | Root Dry Weight (g) | Shoot Fresh Weight (g | Shoot Dry Weight (g) |
|---|---|---|---|---|---|---|---|---|---|
| Variety-1 | 31.40 a | 12.76 a | 8.83 a | 13.20 a | 31.21 a | 0.96 b | 0.56 a | 30.10 a | 18.38 a |
| Variety-2 | 29.83 a | 12.17 a | 9.43 a | 13.68 a | 29.72 b | 1.04 a | 0.60 a | 27.21 b | 16.77 b |
| LSD P= 0.05) | 3.1319 | 1.1396 | 1.2143 | 1.1819 | 1.2652 | 0.0583 | 0.0376 | 1.6465 | 1.4102 |
| **Treatment** | | | | | | | | | |
| T1 | 25.16 c | 9.63 c | 5.35 e | 12.23 b | 24.10 c | 0.73 e | 0.43 d | 21.32 e | 12.59 d |
| T2 | 30.50 bc | 11.33 bc | 9.86 abc | 12.90 ab | 29.50 b | 1.06 bc | 0.56 c | 26.57 d | 17.48 bc |
| T3 | 26.16 c | 13.00 ab | 7.46 de | 12.86 ab | 31.23 ab | 1.08 ab | 0.57 c | 26.85 cd | 14.87 cd |
| T4 | 35.50 ab | 12.63 ab | 8.83 cd | 13.40 ab | 31.53 ab | 0.96 cd | 0.58 bc | 29.99 b | 14.87 cd |
| T5 | 29.00 c | 13.26 ab | 9.20 bcd | 14.36 ab | 32.43 a | 1.18 a | 0.72 a | 29.89 bc | 20.89 a |
| T6 | 29.25 c | 14.16 a | 12.06 a | 14.53 a | 32.70 a | 1.09 ab | 0.65 b | 36.95 a | 18.82 ab |
| T7 | 38.75 a | 13.23 sab | 11.16 ab | 13.80 ab | 31.76 ab | 0.89 d | 0.56 c | 28.99bcd | 18.95 ab |
| LSD (P= 0.05) | 5.8592 | 2.1320 | 2.2718 | 2.2111 | 2.3669 | 0.1091 | 0.0704 | 3.0804 | 2.6383 |

### 3.2 Yield Parameters

Statistically significant differences were found between the two lentil varieties regarding the numbers of pod per plant, 1000-grain weight, and of grain yield whereas the number of grains per pod, biological yield and harvest index did not show a significant (P > 0.05) difference (Table 3.2). Variety-1 yielded significantly more pod number per plant (48.01) and more 1000 grain weight (23.98 g) as compared to the Variety-2 (42.43 pods per plant and 20.42 g 1000 grains respectively). Grain yield also was better for Variety -1 (554.26 kg/ha) than Variety 2 (499.44 kg/ha). Although differences were not statistically significant, both varieties had similar biological yields and harvest indices. INM treatments led to highly significant (P <= 0.05) variation of all the measured yield attributes except of the number of grains pod$^{-1}$. The maximum number of pods plant$^{-1}$ (58.65), grains pod$^{-1}$ (2.06) and biological yield (2996.6 kg ha$^{-1}$) were registered in $T_6$ which also produced a relatively high grain yield (592.19 kg ha$^{-1}$). Treatment $T_7$ showed a similar result with the highest grain yield (700.89 kg ha $^{-1}$), as well as the highest harvest index (24.05%) and 1000 grain weight (23.15 g). On the contrary, the control ($T_1$) recorded the minimum values for most of the traits i.e., pods plant$^{-1}$ (34.13), grains pod$^{-1}$ (1.66), grain yield (335.94 kg ha$^{-1}$) and biological yield (1786.8 kg ha$^{-1}$) indicating a strong and positive response of lentils to integrated nutrient management.

**Table 3.2**

*Effect of INM and varieties on yield parameters*

| Varieties | number of Pods plant$^{-1}$ | number of Grain pod$^{-1}$ | 1000 Grain Weight (g) | Biological yield kg/ha | Grain Yield/ha (kg) | Harvest Index |
|---|---|---|---|---|---|---|
| Variety-1 | 48.01 a | 1.94 a | 23.98 a | 2647.7a | 554.26 a | 20.74 a |
| Variety-2 | 42.43 b | 1.86 a | 20.42 b | 2470.5a | 499.44 b | 20.84 a |
| LSD P= 0.05) | 4.6561 | 0.1456 | 0.8318 | 205.16 | 39.898 | 1.7564 |
| **Treatment** | | | | | | |
| T1 | 34.13 c | 1.66 b | 20.51 b | 1786.8 d | 335.94 d | 19.64 b |
| T2 | 41.81 bc | 1.83 b | 22.26 a | 2643.0 abc | 466.31 c | 18.05 b |
| T3 | 46.93 b | 1.96 a | 22.28 a | 2530.2 c | 492.06 c | 19.71 b |
| T4 | 40.97 bc | 1.96 a | 22.21 a | 2442.4 c | 615.75 b | 25.14 a |
| T5 | 45.64 b | 1.90 ab | 22.63 a | 2589.4 bc | 484.83 c | 19.08 b |
| T6 | 58.65 a | 2.06 a | 22.36 a | 2996.6 a | 592.19 b | 19.86 b |
| T7 | 48.43 b | 1.93 ab | 23.15 a | 2925.0 ab | 700.89 a | 24.05 a |
| LSD (P= 0.05) | 8.7107 | 0.2724 | 1.5561 | 383.82 | 74.642 | 3.2859 |

### 3.3 soil physico-chemical properties

Soil depth made a significant difference in pH, EC, microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) and soil organic carbon (SOC), but had no significant effect on organic matter, total N, available P and available K (P>0.05). The pH was significantly higher (8.11) in the subsurface layer (15-30 cm) than in the surface layer (7.93). Conversely, EC was higher at the topsoil (0.483 dS m-1) and this may be representative of higher concentration of soluble salts near to the top. Biologically, there was significantly higher contents of MBC (71.71 mg/kg), MBN (65.19 mg/kg) and SOC (0.53%) in the 15-30 cm layer than the 0-15 cm. Overall, significant improvement in microbial activity and carbon accumulation was osbserved in subsurface zone. INM treatments had significant (P≤0.05) treatment effects for all the measured soil properties (except organic matter, total nitrogen, available phosphorus, and available potassium). The highest soil pH value was recorded in $T_3$ (8.58) and $T_7$ (8.75) while the lowest soil pH (6.71) was recorded in $T_1$. Electrical conductivity was highly increased by treatments involving integrated nutrient sources especially $T_2$, $T_4$, $T_5$ as compared with control. The highest level of organic matter was found in $T_2$ (0.92%) and $T_6$ (0.88%), which indicates the combined use of organic fertilizer was effective in promoting soil organic enrichment. Although there was no significant difference in total nitrogen, an increase in nitrogen values was observed in the integrated nutrient treatments ($T_2$, $T_5$ and $T_6$). Available phosphorus and potassium also showed small increases in the balanced nutrient treatments with $T_7$ having the highest available P (4.49 mg kg$^{-1}$). Microbial properties showed good and significant improvement under INM. The highest values for the maximum MBC (72.83 mg kg$^{-1}$) and relatively high MBN (65 mg kg$^{-1}$) were recorded in $T_7$ followed closely by treatments $T_2$ and $T_6$. These increases in microbial biomass are indicative of improved functioning of the soil biological system under the combined organic and inorganic nutrient management. Integrated nutrient management also substantially improved soil chemical and microbial attributes over control. Treatments that included organic and inorganic fertilizer (the $T_2$, $T_6$ and $T_7$) improved soil organic matter, nutrient availability, microbial biomass, and SOC content. These improvements help promote better soil fertility, nutrient cycling and long-term soil health, rendering INM an important best management practice for sustainable lentil production systems.

**Table 3.3**

*Effect of integrated nutrient management on soil chemical and soil physico- biological chemical properties at different depths.*

| Soil depth | PH | EC | Organic matter | Total nitrogen | Available phosphorus | Available potassium | MBC | MBN | SOC |
|---|---|---|---|---|---|---|---|---|---|
| **0-15** | 7.93 b | 0.483 a | 0.70 a | 0.03 a | 3.80 a | 111.43 a | 69.81 b | 62.95 b | 0.52 b |
| **15-30** | 8.11 a | 0.389 b | 0.71 a | 0.03 a | 3.83 a | 114.52 a | 71.71 a | 65.190a | 0.53 a |
| **LSD** (P= 0.05) | 0.2201 | 0.0738 | 0.1917 | 0.0100 | 0.1039 | 5.9203 | 1.4473 | 1.3937 | 0.0154 |
| **Treatment** | | | | | | | | | |
| T1 | 6.71 d | 0.38 b | 0.53 c | 0.02 cd | 3.40 e | 95.33 f | 66.50 d | 60.83 e | 0.49 c |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| T2 | 7.57 c | 0.51 a | 0.92 a | 0.04 ab | 3.75 c | 136.33 a | 72.33ab | 63.16cd | 0.54 a |
| T3 | 8.58 a | 0.36 b | 0.56 bc | 0.01 d | 3.56 d | 95.00 f | 71.00bc | 65.33 b | 0.53 ab |
| T4 | 7.72 c | 0.48 a | 0.74 ab | 0.03 bc | 3.75 c | 112.50 d | 70.33 c | 62.66 d | 0.53 ab |
| T5 | 8.11 b | 0.49 a | 0.62 bc | 0.04 ab | 3.88 b | 102.33 e | 71.33bc | 67.16 a | 0.52 b |
| T6 | 8.11 b | 0.40 b | 0.88 a | 0.04 a | 3.81 bc | 121.00 c | 71.00bc | 64.33bc | 0.52 b |
| T7 | 8.75 a | 0.39 b | 0.69 bc | 0.03 c | 4.49 a | 128.33 b | 72.83 a | 65.00 b | 0.54 a |
| LSD (P= 0.05) | 0.1176 | 0.0394 | 0.1025 | 5.353E-03 | 0.0555 | 3.1645 | 0.7736 | 0.7450 | 8.243E-03 |

### 3.4 Correlation Analysis

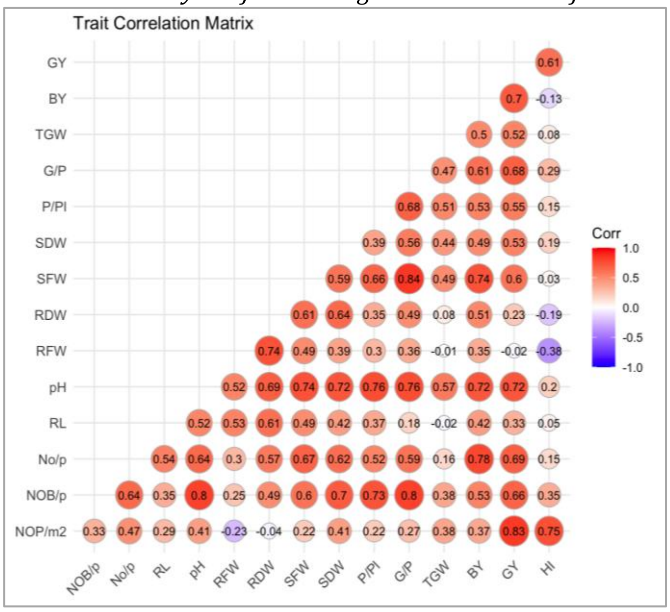
A Pearson correlation matrix was constructed to examine interrelationships among growth and yield parameter in lentil under verities and integrated nutrient management practices (figure 4.4). Grain yield (GY) exhibited strong positive correlations with biological yield (BY, r = 0.83), number of plants per m$^2$ (NOP/m$^2$, r = 0.83), harvest index (HI, r = 0.75), pods per plant (P/Pl, r = 0.78), shoot dry weight (SDW, r = 0.72), and 1000-grain weight (TGW, r = 0.66). These associations indicate that enhanced biomass accumulation, pod set, partitioning efficiency, and seed filling are primary drivers of yield improvement. Biological yield showed strong associations with shoot fresh weight (SFW, r = 0.74) and SDW (r = 0.84), reinforcing the importance of active vegetative development in total productivity.

Root traits such as root fresh weight (RFW), root dry weight (RDW), and root length (RL), were strongly interrelated (r = 0.30-0.74) and exhibited moderate yet positive correlations with grain yield (GY), but negative correlations with harvest index (HI) (e.g., RFW–HI, r = –0.38). This indicates that there could be possible trade-offs in carbon allocation between belowground investment and reproductive efficiency.

Nodulation (nodules per plant No/pl) and branching (NOB/pl) correlated moderately to strongly with GY (r = 0.64–0.78). Weak negative links, such as certain root parameters with HI, highlight allocation constraints under the tested conditions. Overall, the correlation patterns reveal coordinated enhancements in aboveground biomass, pod production, and harvest efficiency as key pathways for yield gains through integrated management.

**Figure 3.1**

*Correlation analysis of various agronomical traits of lentil.*

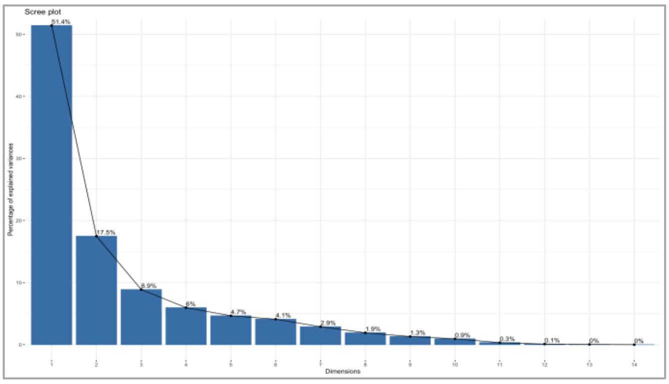



### 3.5 Principal Components Analysis

Principal component analysis (PCA) was performed for fifteen agronomic traits of lentil to investigate multivariate relationships under different integrated nutrient management (INM) treatments. The scree plot indicated that first three principal components i.e., PC1, PC2 and PC3 having eigenvalue greater than one (>1), cumulatively explained 77.76% of the total variance with the individual contribution of 51.4%, 17.5% and 8.9%, respectively of the total variance (Figure 4.1). The remaining components viz., PC4 to PC15 added smaller amount proportion towards the cumulative variance (Table 4.25).

**Figure: 3.2.**

*Scree Plot is displaying the contribution of individual variable trait in total variation.*

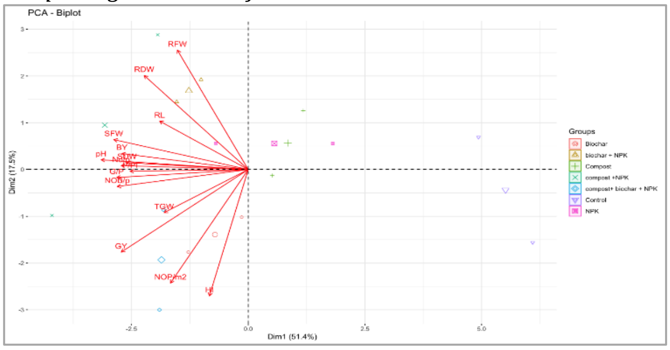



### 3.6: PCA bi-plot for treatments

PCA bi-plot displayed that the first principal component (PC1) is mainly defined by the positive loadings of yield-related traits including grain yield (GY), biological yield (BY), pods per number of plant/m$^2$ (NOP/m$^2$), pods per plant (P/Pl), 1000-grain weight (TGW), and harvest index (HI), reflecting their close interdependence and indicating that improvements in one trait were generally accompanied by gains in the others (figure 4.2). Integrated nutrient management treatments, particularly compost + biochar + NPK and compost + NPK, were positioned in the direction of these yield traits, highlighting their effectiveness in simultaneously enhancing multiple components of productivity (4.2). On the other hand, root traits including root fresh weight (RFW), root dry weight (RDW), and root length (RL) were strongly aligned with PC2, suggesting that treatments like biochar + NPK and compost were more influential in promoting root system development (4.2 ). Shoot fresh and dry weights (SFW, SDW) occupied an intermediate effect by linking vegetative growth with both root and reproductive traits. Moreover, the PC3 was mainly characterized by the strong positive loadings of 1000-grain weight (TGW), pods plant$^{-1}$ (P/Pl) and grain pod$^{-1}$, whereas, on the other hand this PC had few negative loadings including root length (RL) and number of plants/m$^2$ (4.25).

**Figure 3.3**

*PCA biplot for seven treatments ($T_1$ to $T_7$) and 15 morphological traits of lentil.*




### 3.7: PCA biplot for varieties

Furthermore, the PCA biplot of agronomic traits (4.3) demonstrated two clear multivariate gradients for first two essential principal components. The variety ellipses overlap considerably, indicating that variety alone does not completely separate multivariate responses, but the dasht-21 centroid lies closer to the side of the biplot defined by the productivity and root-growth arrows while black lentil panjgur is shifted toward the opposite side. This pattern implies that, on average, dasht-21 attains somewhat higher combined scores for maximum agronomic traits measured (i.e., greater pods numbers, plant biomass and root development), though within variety variation is large. In practical terms, integrated nutrient treatments that scored toward the productivity side of PC1 simultaneously enhanced multiple yield components and biomass, whereas treatments associated with PC2 emphasized below-ground development. The biplot, therefore supports the conclusion that improvements in lentil yield under integrated nutrient management arise from coordinated gains in pods, biomass and root system vigour rather than a single trait change (4.3).

**Figure: 3.4**

*PCA bi-plot for first two principal components with effects of varieties.*

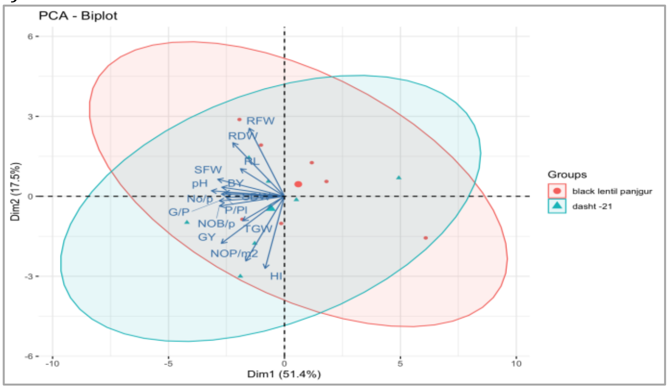



**Table 3.4**

*Correlation analysis of 15 agro-morphological traits of lentil varieties.*

| Trait | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 | PC7 | PC8 | PC9 | PC10 | PC11 | PC12 | PC13 | PC14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NOP/m2 | -0.179 | -0.446 | -0.302 | 0.249 | 0.188 | -0.073 | 0.112 | 0.150 | 0.212 | 0.115 | 0.180 | 0.195 | 0.577 | 0.198 |
| NOB/p | -0.301 | -0.067 | 0.059 | -0.404 | -0.097 | 0.119 | -0.433 | 0.092 | -0.104 | -0.496 | 0.232 | 0.141 | 0.210 | -0.304 |
| No/p | -0.292 | 0.015 | -0.246 | 0.213 | -0.358 | 0.321 | -0.247 | -0.077 | 0.271 | 0.351 | 0.348 | -0.357 | -0.205 | -0.138 |
| RL | -0.203 | 0.190 | -0.503 | 0.137 | 0.021 | -0.534 | -0.086 | -0.322 | -0.151 | -0.348 | 0.156 | -0.084 | -0.154 | 0.220 |
| PH | -0.338 | 0.038 | 0.064 | -0.084 | 0.176 | -0.164 | -0.041 | 0.393 | -0.204 | 0.071 | -0.295 | -0.697 | 0.192 | 0.050 |
| RFW | -0.163 | 0.470 | -0.097 | -0.122 | 0.146 | -0.151 | 0.374 | 0.397 | 0.524 | -0.089 | 0.120 | 0.121 | -0.122 | -0.236 |
| RDW | -0.239 | 0.370 | -0.194 | -0.102 | 0.186 | 0.165 | 0.049 | 0.055 | -0.582 | 0.463 | 0.139 | 0.338 | 0.048 | -0.023 |
| SFW | -0.309 | 0.118 | 0.150 | 0.070 | -0.148 | 0.008 | 0.409 | -0.595 | 0.014 | -0.015 | -0.252 | -0.071 | 0.319 | -0.337 |
| SDW | -0.278 | 0.027 | -0.112 | -0.116 | 0.546 | 0.372 | -0.263 | -0.273 | 0.323 | -0.041 | -0.354 | 0.084 | -0.109 | 0.177 |
| P/Pl | -0.272 | -0.007 | 0.268 | -0.193 | -0.285 | -0.513 | -0.327 | -0.028 | 0.227 | 0.407 | -0.184 | 0.297 | 0.021 | 0.118 |
| G/P | -0.302 | -0.031 | 0.248 | -0.300 | -0.214 | 0.213 | 0.385 | -0.036 | -0.004 | -0.129 | 0.286 | -0.046 | -0.049 | 0.631 |
| TGW | -0.193 | -0.169 | 0.527 | 0.263 | 0.486 | -0.199 | -0.012 | -0.122 | -0.057 | 0.047 | 0.453 | -0.045 | -0.234 | -0.168 |
| BY | -0.290 | 0.063 | 0.105 | 0.528 | -0.212 | 0.147 | -0.013 | 0.256 | -0.103 | -0.249 | -0.127 | 0.220 | 0.095 | -0.107 |
| GY | -0.292 | -0.325 | -0.064 | 0.155 | -0.102 | 0.017 | 0.143 | 0.181 | -0.139 | -0.087 | -0.349 | 0.198 | -0.546 | 0.029 |
| HI | -0.089 | -0.497 | -0.283 | -0.400 | 0.017 | -0.087 | 0.275 | -0.024 | -0.064 | 0.112 | 0.034 | -0.025 | -0.156 | -0.381 |
| *Std. Dev.* | 2.777 | 1.619 | 1.154 | 0.946 | 0.835 | 0.785 | 0.658 | 0.536 | 0.444 | 0.376 | 0.220 | 0.118 | 0.077 | 0.000 |
| *Prop. Var.* | 0.514 | 0.175 | 0.089 | 0.060 | 0.047 | 0.041 | 0.029 | 0.019 | 0.013 | 0.009 | 0.003 | 0.001 | 0.000 | 0.000 |
| *Cum Prop:* | 0.514 | 0.689 | 0.778 | 0.837 | 0.884 | 0.925 | 0.954 | 0.973 | 0.986 | 0.995 | 0.999 | 1.000 | 1.000 | 1.000 |
| *Eigenvalue* | 7.711 | 2.622 | 1.331 | 0.895 | 0.698 | 0.616 | 0.433 | 0.288 | 0.197 | 0.141 | 0.048 | 0.014 | 0.006 | 0.000 |
| *Cum.Variance* | 51.41 | 68.89 | 77.76 | 83.73 | 88.38 | 92.49 | 95.37 | 97.29 | 98.6 | 99.54 | 99.87 | 99.96 | 100 | 100 |

Std. Dev: Standard Deviation; Prop. Var: Proportion of Variance; Cum Prop: Cumulative Proportion; Cum.Variance: Cumulative Variance

## 4.DISCUSSION

### 4.1 growth parameter

Significant genotypic differences between the two lentil varieties in plant height, shoot fresh and dry weights, and root fresh weight reflect contrasting biomass partitioning strategies. Variety 1's superior aboveground traits suggest greater photosynthetic allocation and vigor, while Variety 2's higher root fresh weight (and trends in nodule number and root dry weight) indicate enhanced belowground investment, potentially aiding nutrient acquisition in stressful conditions. Such variability in root and shoot traits among lentil genotypes is well-documented, with some prioritizing shoot biomass for yield potential and others root systems for stress adaptation (Gorim and Vandenberg, 2017; Purushothaman et al., 2024).

The INM treatments marked different responses with $T_6$ leading in plant density, branching, nodulation, and shoot biomass, while $T_5$ led in height and root dry weight. Marked synergistic effects from the mixture of organic, inorganic, and bio-inputs were seen. All the treatments except $T_1$, the control, were statistically different across most traits. Because $T_1$ did have some inorganic and organic nutrients, it shows the effect of the combined nutrients, microbial, and nitrogen fixing impacts of the treatments. Recent studies verify the synergistic effect of INM with vermicompost, biofertilizers, and balanced fertilizers on nodulation, biomass, and growth of lentils due to improved soil and biological fertility (Kumar et al., 2023; Kumar et al., 2025; Bhattacharyya et al., 2025). The lack of significant variation in root length suggests that this trait may be under stronger genetic control.

The overall results confirm INM's worth for sustainable lentil intensification as it promotes vigorous growth and nodulation, which is particularly effective in nutrient-poor soils.

**4.2 yield parameter**

The differences in variatal average number of pods per plant, 1000-grain weight, and grain yield from Variety 1 and 2. show the impacts of different genotype on the essential components of yield. The grain yield of Variety- 1 was likely due to the greater number of pods and larger seeds which is indicative of greater sink strength and assimilate partitioning. The differences in yield of lentil genotypes is well documented. The macrosperma of lentils is a type that had been found in optimal conditions to have greater and more pods than the other lentil types and thus, had a greater yield potential (Purushothaman et al., 2024). The lack of statistical significance across the variety with relation to grains per pod, biological yield, and harvest index is suggestive of these traits being similarly or more buffered across the tested environmental variables.

The highest achievement of $T_7$ was observed in the harvest index, gain yield, and in 1000-grain weight, while $T_6$ outperformed the others in the number of pods per plant, grains per pod, and biological yield. Almost all the control treatments ($T_1$) have low values, demonstrating the responsive synergism of organic matter, biofertilizer, and chemical fertilizers to overcome the nutrient related reproductive development and partitioning improvement. INM coupled with vermicompost and less chemical fertilizers has been documented to provide significant yield improvements (50%) and better harvest indices in lentils due to the improved nutrient and soil biology chik (Kumar et al., 2023; Meena et al., 2024). The lesser response in grains per pod is expected due to the high genetic factor that control it.

Overall, these findings strengthen the case for INM's efficacy in sustainably increasing lentil productivity, particularly in the enhancement of pod set, seed filling, and biomass conversion, thereby providing actionable strategies for soils deficient in nutrients.

**4.3: soil parameter**

The atypical response of pH, EC, MBC, MBN, and SOC to changes in soil depth, showing MBC 71.71 mg $kg^{-1}$, MBN 65.19 mg $kg^{-1}$, and SOC 0.53% and higher pH (8.11) in the deeper layer (15-30 cm) than the upper layer (0-15 cm) is unusual in agricultural soils, which tend to show pH, moisture, and microbial biomass (MBC) enrichment in the upper profile due to organic amendments and fibrous root proliferation. The described conditions could, in part, be attributed to the restricted surface disturbance, which minimizes oxidation, less downward leaching of salts, and greater microbial and root carbon protection in the deeper layers from surface microbial stresses. higher MBC along with temperature and moisture desiccation (Stone and Plante., 2022; Evrendilek et al., 2004). The greater surface EC (0.483 dS $m^{-1}$) observed in the surface (0-15 cm) soil likely indicates that salts which may have been trapped from evaporation or from the used fertilizers. The minimal or absent effects of depth on the distribution of organic matter, total N, available P, and K suggests uniformity which could have been an effect of previous management and/or rhizodeposition from the legumes.

There were some notable changes in the treatments, with the exception of organic matter, total N, available P, and K. Treatments T3 (8.58) and T7 (8.75) had an increase in pH, integrated sources ($T_2$–$T_5$) had an increase in EC, and T2 (0.92%) and T6 (0.88%) had peak values of organic matter. There were notable increases in microbes, with $T_7$ having the highest (72.83 mg $kg^{-1}$ MBC) followed by $T_2$ and $T_6$. Trends toward higher total N in ($T_2$, $T_5$, $T_6$) and available P in $T_7$ (peak 4.49 mg $kg^{-1}$) suggest that organic inputs were supplying labile substrates that stimulated microbial growth and nutrient mineralization. This also decreased pH due to the presence of organic acids (Meena et al., 2024; Dotaniya et al., 2023).

The results emphasize that INM is a better alternative than the control and increasing biological activity, SOC accumulation, and improved fertility. This is all the reason why it is suggested that resilient lentil systems in alkaline-prone soils are achievable with improved nutrient cycling.

**4.4: correlations analysis**

The strong positive correlations between grain yield and biological yield, harvest index, pods per plant, plant density, shoots biomass, and seed weight are well-documented for lentils and per some researchers, though, under conditions of nutrient fluctuation, productivity is primarily driven by sink reproductive strength and assimilate partitioning (Bhattacharyya et al., 2025; Choukri et al., 2025). The high correlation between biological yield and shoots reaffirms that active and vigorous shoot growth influences and promotes a higher retention and filling of pods, as noted under integrated inputs in rice-lentil systems (Bhattacharyya et al., 2025; Kumar et al., 2023).

The moderate intercorrelations among root traits and the yield suggest conserved belowground structures and trade-offs in aboveground partitioning with harvest index in high-yielding situations inter correlated suggesting the modern lentil breeding trend where high root biomass in optimal nutrition breeding conditions is counterproductive to root to reproduction efficiency (Purushothaman et al., 2024). The positive relationship between yield and nodulation reinforces the INM symbiotic benefit.

These interrelations indicate integrated nutrient management (INM) approaches increase yield as the result of improved biomass, pod, and partitioning. This also provides indirect criteria for selection to breed robust genotypes in nutrient deficient environments.

**4.5 Principal component analysis**

Analysis of fifteen agronomic traits via principal component analysis revealed that the first three components captured 77.76% of the total variation. The first principal component (51.4%) was yielded dominated (biological yield, grain yield, plant density, 1000-grain weight, pods per plant, harvest index), and reflects, lentil multivariate analysis, (Idrissi et al., 2024; Zeroual et al.,

2025) and the close relationship of the components of interdependence productivity. The treatments that combine compost + biochar + NPK and compost + NPK had strong positive loadings on PC1, illustrating these treatments the potential to improve nutrient availability and partitioning to increase several yield components.

PC2 (17.5%) focused on root metrics (fresh/dry root weights, root length), where the treatments with biochar + NPK and compost promoted belowground rooting, showcasing the trade-offs in allocation under different integrated nutrient management (INM) practices (Purushothaman et al., 2024). Apart from this axis, shoot biomass traits linked vertically and drove the positive responses in the rest of the axis. PC3 (8.9%) focused on seed-filling attributes and contrasted it with root length and density.

The varietal biplots showed quite a bit of overlap, which suggests that the effects of INM practice were larger than the effects of the genotype, although Dasht-21 centroid did edge higher on the productivity and root length axes. PCA showed that the greatest contributions to the sustained yield increase from the INM practices were from positive synergies in biomass, pod setting, pod partitioning, and root setting, which highlights the value of indirect trait selection for the sustainable management of lentils (Choukri et al., 2025; Sardar et al., 2025).

## CONCLUSION

Integrated Nutrient Management (INM), especially $T_7$ (half compost + half biochar + half NPK), has shown positive results concerning lentil productivity and soil improvements for semi-arid Quetta conditions. This treatment gave the highest seed yield (950 kg $ha^{-1}$) and recorded the highest growth and nodulation parameters. Additionally, there were significant improvements in post-harvest soil parameters (organic carbon 0.95%, bulk density, and available N, P, K) achieving ≈40% higher yields over the control and 15–18% higher than individual full amendments. Dasht-21 has also shown better results over Black Lentil Panjgur which indicates the possible merit for varietal specific INM packages.

The synergistic combination of organic and inorganic sources is climate-smart and allows the reduction of the dependence of chemical fertilizers, the restoration of degraded soils, and the improvement of food security in the drylands of Balochistan and beyond. Though based on one season, the results support the recommendation of $T_7$ as a practical option for lentil growers. It is recommended that multi-season and multi-location trials, as well as studies on the dynamics of microorganisms and the long-term effects of biochar, be conducted to further support and refine these findings.

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