Zoo Botanica
ISSN: 3007-2050 (E), 3007-2042 (P)

Check for updates

Research Article

Effect of mulch and biofertilizers on forage and seed yield of italian ryegrass

Hussain Ahmad[1], Waleed Azhar[1], Syed Tanzeel Husnain[1], Syed Awais Hussain Shah[1], Khawar Abbas[1], Muhammad Owais Dogar[1], Zain ul Sajjad[1], Zuhair Husnain[1], Mahmood-ul-Hassan[2]

[1]Department of Agronomy, Faculty of Agriculture, Pir Mehr Ali Shah, Arid Agriculture University Rawalpindi, Pakistan.

[2]Department of Plant Breeding and Genetics, Faculty of Agriculture, Pir Mehr Ali Shah, Arid Agriculture University Rawalpindi

ABSTRACT

In semi-arid regions, Italian ryegrass (*Lolium multiflorum*) serves as a crucial forage crop with its productivity reduced because of deficient soil water resources and poor nutrient conditions. The sustainable production of forage seeds along with plant seeds depends heavily on resolving these key issues in resource-limited areas. This research evaluated the synergistic impacts between using mulch with biofertilizers on Italian ryegrass soil conditions and vegetation growth and seed and forage yield development. Researchers conducted a two-year outdoor trial (2023-2025) in the research facilities of PMAS Arid Agriculture University Research Farm Rawalpindi through Randomized Complete Block Design (RCBD) while working with three duplicate units. The research implemented seven treatments that included Control as T1 and combination treatments as T2 through T7 which were Mulch, Bio-fertilizer, Fertilizer, Mulch + Fertilizer, Mulch + Bio-fertilizer, Mulch + Fertilizer + Bio-fertilizer. Standard methods allowed researchers to measure both the soil properties such as moisture, mineral nitrogen, extractable potassium, and available phosphorus and agronomic parameters like plant height, tillers, biomass, grain yield, crude protein, fixed protein in the studied area. The researchers used ANOVA together with LSD and correlation analysis for their statistical evaluations. The combination of Mulch and Fertilizer endowed with Bio-fertilizer (T7) created significant soil moisture increase by 17.33% and raised mineral nitrogen levels by 52.50 mg/kg and extractable potassium by 259.17 mg/kg and available phosphorus by 102.50 mg/kg above control levels ($P < 0.0001$). Total plant height reached 5.83 cm and the maximum tillers per plant numbered 6.33 in treatment T7 which also resulted in the best fresh biomass output at 5688.8 kg/ha and highest dry matter yield at 1427.3 kg/m² and final grain yield of 17.57 g/m². The percentage of crude protein rose to 1.80%, but the crude fiber content lowered to 5.00% which shows enhanced forage quality. High and positive relationships ($r > 0.96$) were detected between water content, nutrient availability, yield measurement variables, yet crude fiber exhibited negative correlations ($r = -0.94$). Research findings show that combining mulch with bio-fertilizers through T7 application method leads to outstanding improvements in Italian ryegrass soil health and plant expansion, resulting in superior forage and seed production yields. The authors underline integrated nutrient management as a promising approach for enhancing productivity and forage quality, specifically in semi-arid regions among farmers who operate with constrained resources.

Keywords: Biofertilizers; forage crop; italian ryegrass; livestock.

OPEN ACCESS

Correspondence
Hussain Ahmad
qazihussain53@gmail.com
Zain ul sajjad
Zainulsajjad.edu@gmail.com

Article History
Received: March 24, 2025
Accepted: August 24, 2025
Published: August 31, 2025

INTRODUCTION

Italian ryegrass (*Lolium multiflorum* Lam.) demonstrates popularity among forager crop producers because of its exceptional nutritional value and fast growth rates alongside its capacity to thrive across many environmental zones. The production system of temperate animals relies on Italian ryegrass in two functions it provides

both animal feed and plant seeds so it significantly adds to global livestock agriculture (Xie et al., 2021; Sajjad et al., 2024). The increasing market demand for animal products and necessity of sustainable forage production makes it essential to improve Italian ryegrass forage crops both in productivity and resilience (Vanvanhossou et al., 2021). The sustainable improvement of crop yields and soil health requires agro-efficiency strategies where mulching and biofertilizer usage has become prominent (Ray & Bharti, 2023).

The soil surface covering method known as mulching uses both organic and inorganic materials to preserve water content in the soil besides managing temperatures and weed control and providing continuous nutrients through decomposition (Beltagi et al., 2022). Bio-fertilizers gain their nutrient-enhancing potential from beneficial microorganisms including Rhizobium and Azospirillum among nitrogen fixers and Pseudomonas and Bacillus as phosphorus solubilizers and contribute to soil health improvement and improved plant growth according to Nosheen et al. (2023). Through the combined use of mulching along with bio-fertilizers, it becomes possible to achieve superior results for Italian ryegrass yield and quality. The complete evaluation of these agricultural practices on soil productivity together with their influence on field crop growth along with harvest results requires more investigation (Murtaza et al., 2023).

Beside the Italian region, the crop is cultivated in North American and European regions as well as other parts of Asia due to the crop's ability to grow rapidly. The crop also enhances soil organic matter. Its rapid growth rate allows for several harvests during a single growing season (García et al., 2021). Though, the regions face several challenges including soil fertility reduction, climatic changes, and water shortage. To increase productivity in these regions, innovative changes such as bio-fertilization need to be implemented. The Italian rye grass is considered the most productive as it is very adaptable to both intensive and extensive diverse farming systems (Imran et al., 2022). Bio mulch and irrigation also need to be employed. It is alarming to see that livestock production makes up bulk of crops agricultural output, forcing farmers to rely on forage. As stated by FAO, the increasing dependency on forage livestock systems is troubling as it makes pasture and crop cultivation for livestock of utmost importance (Rao et al., 2015). In addition to all these confirms, the rye grass is preferred as forage due to its rich contents of crude protein and its increased digestibility as well as it's pleasant taste' (Poudel et al., 2022).

The use of mulching and bio fertilizers promote ecological agriculture because they provide solutions for increasing productivity while preserving the environment (Nandita et al., 2024). For instance, mulching helps to retain moisture, control soil erosion, and moderate temperatures, which contributes towards solving issues of water shortage and soil deterioration (Wang et al., 2021). In the same way, bio-fertilizers help to decrease the use of chemical fertilizers, which in turn helps to reduce emissions of greenhouse gasses while improving soils biological activity (Devi et al., 2022). Besides its productive use in Forage, Italian ryegrass also has high economic value being a seed crop with great yield prospects in both the local and export markets (Shilomboleni et al., 2023). Its production systems sustainability is however jeopardized by soil depletion, variable weather, and excessive dependence on traditional methods like chemical fertilizers and irrigation (Mclennon et al., 2021). While the advantages associated with the use of mulching and bio-fertilizers have been studied separately in detail, their synergistic use in the cultivation of Italian ryegrass is one of the least studied aspects (Alharbi et al., 2024).

Additionally, the effectiveness of these practices relies on specific agro-ecological zones, which require individual assessments for their efficient practice to be achieved optimized (Hussain et al., 2024). While much work has been done on the impact of mulching and bio-fertilizers on different crops, the focus on their combined application in forage crops, especially on Italian ryegrass, is scant (Janardhan & Krishna, 2021). Most of the existing research is focused on the immediate harvest yield increases without consideration for the soil health as well as the stability of the ecosystem system in the longer term (Young et al., 2021). Moreover, the use of different types of mulch, varying formulations of bio-fertilizers, and applications of differing rates of bio-fertilizers emphasizes the necessity for best practices in managing the environment (Meddich et al., 2020).

Research Questions

1. What synergistic effects do mulching and bio-fertilizers have on the growth, forage yield, and seed yield of Italian ryegrass?
2. How do different mulch and bio-fertilizer treatments work for different soil plant nutrient status and growth responses?
3. How do the combined application of mulching and bio-fertilizers reduce some abiotic stresses like droughts in the cultivation of Italian ryegrass?

Mulching paired with bio-fertilizers boosts Italian ryegrass in forage and seed. Richer dirt nutrients, water that lingers longer, and plants that scoop up feed fast all play a part. It works, plain and simple.

The main objective of this study to evaluate the effects of different mulch types on the growth and productivity of Italian ryegrass. To assess the impact of bio-fertilizers on soil nutrient availability and plant growth. To investigate the interaction between mulching and bio-fertilizer applications on forage and seed yield. To develop sustainable recommendations for Italian ryegrass cultivation across diverse agro-ecological conditions. We ran field trials and crunched tough numbers to see how our treatments shake up the crop and soil. Real data met hands-on dirt work, giving us tips that farmers, ag buffs, and even policy heads can run with. In the end, our work lifts food security on a global scale and nudges farming toward a greening, neighborly vibe.

MATERIALS AND METHODS

The research took place across two winter seasons between the 2023-2024 and 2024-2025 academic years at the PMAS Arid Agriculture University Research Farm situated in Koont on Chakwal Road in Rawalpindi. The experimental site possesses semi-arid climatic features and registers an average annual rainfall of 560 mm together with a long-term seasonal temperature average of 29.88°C. The agricultural site is situated at the coordinates of 32.9303° N for latitude and 72.8558° E for longitude. The experiment used a Randomized Complete Block Design (RCBD) with triple replications and utilized a three-factorial randomization method. Each of the seven treatments received three replications with a dedicated experimental area measuring 25 m² for each treatment. The ground was ploughed twice during seedbed preparation which depended on the levels of soil moisture. The agricultural team drilled Italian ryegrass seeds into the soil at a depth of 2.5 cm to maintain proper moisture levels for successful germination.

The experiment comprised seven treatments: The seven treatment categories included T1 as Control and T2 with Mulch and T3 with Bio-fertilizer and T4 with Fertilizer and T5 with Mulch plus Fertilizer and T6 with Mulch plus Bio-fertilizer and T7 with Mulch plus Fertilizer plus Bio-fertilizer. Standardized methods were applied to measure soil parameters like soil pH, electrical conductivity (EC), moisture content, mineral nitrogen, extractable potassium, and available phosphorus. Soil pH levels were established through the slurry method whereas EC levels were determined using an EC meter. The gravimetric method assessed soil moisture content and mineral nitrogen extraction was done through a KCl solution. Flame photometry determined extractable potassium while Olsen's method assessed available phosphorus. The research measured agronomic traits including plant height and number of tillers as well as fresh biomass yield and dry matter yield and grain yield of Italian ryegrass. The Kjeldahl method determined crude protein and AOAC 962.09 method analyzed crude fiber as quality parameters.

Quantitative data were contrasted using descriptive statistics in the form of mean and standard error. Inferential statistical tests were used to contrast the effects of the treatments. Analysis of Variance (ANOVA) was used to contrast the overall effects of the treatment. Least Significant Difference (LSD) test was used to conduct pair-wise contrasts. Regression and correlation analysis were used to investigate the correlations between the variables. All the statistical tests were conducted using either SPSS or R software. The research had ten significant parameters of Italian ryegrass plant growth, seed yield, forage production, and soil health that were assessed under the effects of bio-fertilizer and mulch application.

RESULTS AND DISCUSSION

Soil Moisture

Soil moisture content was also significantly impacted by mulch and bio-fertilizer applications. The highest moisture retention was observed in T7 (17.33%), followed by control (T1) with 11.05%. Mulch was responsible for controlling evaporation, while bio-fertilizers enhanced soil structure and thereby the water retention ability. Annual measurements indicated steady increments, with T7 showing 17.57% in 2024 and 17.10% in 2023. ANOVA results indicated significant effects of year ($F = 81.65$, $P < 0.0001$) and treatment ($F = 1660.76$, $P < 0.0001$), but no interaction was significant ($P = 0.4890$). Low coefficient of variation (CV = 0.92%) indicated high precision of measurements taken. These findings indicate the crucial contribution of integrated soil management practices toward maintaining optimal levels of moisture, which are critical in sustaining intensive plant growth and maximizing yield potential under semi-arid conditions.

Mineral Nitrogen

Mineral nitrogen content in the soil increased progressively with the use of mulch and bio-fertilizers. T7 had the highest nitrogen content (52.50 mg/kg) and T1 the lowest (22.00 mg/kg). Yearly observation noted T7 as 53.67 mg/kg in 2024 and 51.33 mg/kg in 2023. ANOVA values indicated significant year ($F = 392.45$, $P < 0.0001$) and treatment ($F = 6402.54$, $P < 0.0001$) effects, but no significant interaction ($P = 0.4579$). The rise in nitrogen availability is due to increased nitrogen fixation by bio-fertilizers and decreased leaching by mulch. These findings indicate the significance

of integrated nutrient management for enhancing soil fertility and plant growth. The low CV (0.88%) also validated the precision of the data, highlighting the effectiveness of these practices to increase nitrogen availability for maximum crop performance.

Extractable Potassium

Maximum extractable potassium content was in T7 (259.17 mg/kg) and minimum in T1 (155.33 mg/kg). Annual measurements positioned T7 at 261.67 mg/kg in 2024 and 256.67 mg/kg in 2023. ANOVA analysis indicated that there was significant year ($F = 20.21$, $P = 0.0001$) and treatment ($F = 1340.80$, $P < 0.0001$) effects, but no significant interaction ($P = 0.4434$). The enhanced availability of potassium is attributed to enhanced nutrient mineralization and leaching reduction by mulch and bio-fertilizers. Potassium is an essential nutrient that plays a key role in plant stress tolerance, enzyme activation, and water management. The results underscore the importance of potassium in improving plant resilience and potential yield. The CV of 1.19% reflected precision in the measurement, further proof of the efficiency of integrated nutrient management in maximizing potassium availability.

Phosphorus Availability

The content of available phosphorus was much greater in T7 (102.50 mg/kg) than in T1 (76.83 mg/kg). Trends observed over time indicated that T7 reached 156.33 mg/kg in 2024 and 152.33 mg/kg in 2023. The analysis of variance (ANOVA) results indicated significant effects of year ($F = 9.6E+30$, $P < 0.0001$), treatment ($F = 3.3E+32$, $P < 0.0001$), and their interaction ($F = 11.41$, $P < 0.0001$). The increase in phosphorus availability is due to increased solubilization by biofertilizers coupled with additional assistance from improved soil structure as a result of the application of mulch. Phosphorus plays a critical role in root development, energy transfer, and reproductive growth in plant systems. These findings indicate the crucial role played by phosphorus in optimizing agricultural productivity. The increasing trend in phosphorus values over successive years further underscores the long-term advantage of integrated nutrient management practices in soil fertility maintenance and crop yield improvement.

Plant Height

The treatments had significant impacts on plant height, with T7 registering the highest plant height of 5.83 cm against T1 with plant height of 2.16 cm. Yearly measurements indicated that the T7 plants achieved heights of 103.33 cm in 2024 and 101.67 cm in 2023. The ANOVA revealed significant year ($F = 168.54$, $P < 0.0001$) and treatment ($F = 2875.48$, $P < 0.0001$) effects but no significant interaction ($P = 0.7132$). The low coefficient of variation of 0.43% confirmed the reliability of the measurements. The increase in plant height indicates improved nutrient supply and soil water retention, both of which are essential for optimal forage and seed yields. Increased plant height is associated with increased biomass production and better light interception, thus overall increased crop productivity. The findings emphasize the importance of integrated nutrient management in promoting healthy vegetative growth.

Tillers Per Plant

Application of mulch and bio-fertilizers resulted in a remarkable increase in the number of tillers per plant. Maximum mean number of tillers (6.33) was exhibited by treatment T7, whereas the minimum (2.16) was exhibited by treatment T1. Data on annual basis depicted that T7 achieved 6.33 tillers per plant in 2024 and 5.33 tillers per plant in 2023. Analysis of variance (ANOVA) results indicated significant effects due to year ($F = 15.26$, $P = 0.0006$) and treatment ($F = 63.93$, $P < 0.0001$), but no significant interaction effect ($P = 0.1781$). The high coefficient of variation (CV) value of 8.94% depicts variability, which may be due to environmental factors. The increase in number of tillers depicts increased vegetative growth, thus increasing biomass production and seed yield. Tillering plays a crucial role in controlling forage yield as it has direct influence on the number of productive shoots. These findings depict the significance of integrated nutrient management practices for maximum tiller production and agricultural productivity.

Fresh Biomass Production

Maximum yield of fresh biomass was recorded in T7 (5688.8 kg/ha), while the minimum was recorded in T1 (3148.8 kg/ha). Annual means indicated that T7 recorded 5706.7 kg/ha in 2024 and 5671.0 kg/ha in 2023. ANOVA results indicated significant year ($F = 11.02$, $P = 0.0027$) and treatment ($F = 941.49$, $P < 0.0001$) effects, and no significant interaction was observed ($P = 0.6889$). The low coefficient of variation (1.51%) further vindicated the validity of the data. The biomass yield increase is an indication of the synergistic effects realized from improved soil moisture and nutrient supply, which are key in optimizing forage production. Fresh biomass is a fundamental indicator of quantifying both the quantity and quality of forage since it has a direct impact on livestock nutrition. The observations indicate the significance of the use of integrated nutrient management practices in improving forage productivity.

Dry Matter Yield

Dry matter yield also followed the same pattern, with T7 having the highest yield (1427.3 kg/m²) and T1 experiencing

the lowest (698.7 kg/m²). Annual values indicated T7 to have 1432.0 kg/m² in 2024 and 1422.7 kg/m² in 2023. ANOVA results indicated significant treatment effects ($F = 258.65$, $P < 0.0001$) but not significant year effects or interaction ($P > 0.05$). CV of 3.44% indicated good precision in the measurements. The rise in dry matter yield indicates the efficiency of integrated nutrient management in improving forage quality and storage capacity. Dry matter yield is an important parameter in determining the nutritional quality of forage because it is a measure of the non-water content of biomass. These findings indicate the usefulness of optimizing nutrient management for sustainable forage production.

Grain yield

Grain yield was maximum in T7 (17.57 g/m²) and minimum in T1 (11.27 g/m²). Annual values showed T7 to have yielded 156.33 g/m² in 2024 and 152.33 g/m² in 2023. ANOVA analysis showed significant year ($F = 15.66$, $P = 0.0005$) and treatment ($F = 3131.75$, $P < 0.0001$) effects, but no significant interaction ($P = 0.1506$). The low CV (1.12%) guaranteed the data to be reliable. The increase in grain yield reflects improved nutrient supply and plant growth, which are required to maximize seed production. Grain yield is a key parameter to measure crop reproductive success, as it directly affects seed availability for planting. The results underscore the significance of integrated nutrient management in maximizing seed production.

Crude Protein

Crude protein content was much higher with the use of mulch and bio-fertilizers. T7 had the greatest protein content (1.80%), while T1 had the least (0.85%). Annual figures gave T7 the highest of 15.90% in 2024 and 15.70% in 2023. ANOVA results demonstrated significant year ($F = 84.94$, $P < 0.0001$) and treatment ($F = 8561.75$, $P < 0.0001$) effects but no significant interaction ($P = 0.7808$). The low CV (0.52%) indicated high reliability. The rise in crude protein content indicates the high potential of integrated nutrient management for improving forage quality and feeding animals. Crude protein determines the nutritional quality of forages since it exerts a direct influence on the growth and productivity of animals. These findings identify the need for optimizing nutrient management for sustainable production of livestock.

Crude Fiber

The crude fiber content had an inverse correlation with mulch and bio-fertilizer use, decreasing progressively from treatment T1 to T7. The maximum crude fiber content of 3.85% was obtained by treatment T1, and the lowest value of 5.00% was observed in treatment T7. Annual observations revealed that T7 had crude fiber contents of 31.77% in 2024 and 31.27% in 2023. The ANOVA results revealed significant effects due to the year ($F = 38.91$, $P < 0.0001$), treatment ($F = 1949.44$, $P < 0.0001$), and their interaction ($F = 5.56$, $P = 0.0008$). The coefficient of variation (CV) was extremely low at 0.31%, which reflects the precision of the measurements. The observed decrease in crude fiber content reflects a corresponding increase in forage digestibility and overall quality. Crude fiber is composed of cellulose, hemicellulose, and lignin, which are less digestible and could lower the nutritional value of forage. The decrease in fiber content corresponding to increased levels of mulch and bio-fertilizer use is likely due to increased nutrient availability and balanced plant growth, resulting in a decreased proportion of structural carbohydrates in the biomass. These results reflect the efficacy of integrated nutrient management in enhancing forage quality, rendering it more palatable and digestible to livestock, thereby contributing positively to animal productivity and health.

Correlation Analysis

The correlation matrix showed significant interdependencies among yield traits, plant growth, nutrient availability, and soil moisture. Except for crude fiber content, which had a marked negative correlation ($r = 0.938$), soil moisture had strong positive associations with all measured variables. Encouraging nutrient availability and plant growth depends much on moisture, which correlated strongly with available phosphorus ($r = 0.985$), plant height ($r = 0.987$), and fresh biomass ($r = 0.985$). Mineral nitrogen strongly positively correlated with extractable potassium ($r = 0.992$), available phosphorus ($r = 0.992$), and grain yield ($r = 0.992$), therefore nitrogen availability is closely related to the uptake and assimilation of other essential nutrients. Given the effect of vegetative growth on biomass accumulation and nutrient content, plant height showed close correlations with fresh biomass ($r = 0.997$), crude protein content ($r = 0.996$), and grain yield ($r = 0.992$). Tillers per plant also showed strong associations with dry matter yield ($r = 0.996$) and fresh biomass ($r = 0.988$), highlighting the contribution of tillering to forage productivity. The strong correlation between fresh biomass and grain yield ($r = 0.991$) indicates that treatments stimulating vegetative growth positively impacted reproductive output. Since dry matter yield strongly and positively correlates with mineral nitrogen ($r = 0.990$) and tillers per plant ($r = 0.996$), the integrated interaction of plant architecture and nutrient availability on yield development is stressed. High correlations between crude protein content kept and grain yield ($r = 0.999$) and plant height ($r = 0.996$) show that enriched treatments improved both yield quality and quantity. On the other hand, crude fiber content had uniform negative correlations across all variables, most notably with plant height ($r = 0.972$), fresh biomass ($r = 0.968$), and crude protein ($r = 0.960$), therefore implying that greater growth and nutrient absorption lower fiber concentration and might therefore improve forage digestibility. These results reveal how much mulch and biofertilizers work together

to improve soil moisture retention and nutrient dynamics, hence increasing the growth and yield of Italian ryegrass. The good associations among soil moisture, nutrient availability, plant growth parameters, and yield components support the finding that integrated nutrient management plans can meaningfully raise both forage and seed yield in addition to concurrently improving forage quality by lowering crude fiber content. These findings offer a strong starting point for the creation of sustainable farming methods aimed at optimizing output and resource use efficiency in Italian ryegrass growing.

Table 1. Soil properties and plant growth parameters.

Treatment	Year	Soil Moisture (%)	Mineral Nitrogen (mg/kg)	Extractable K (mg/kg)	Available P (mg/kg)	Plant Height (cm)	Tillers per Plant
T1	2023	10.83	21.33	155.33	76.83	2.16	2.16
T1	2024	11.27	23.00	157.33	73.33	2.33	2.33
T2	2023	13.10	27.67	175.00	84.17	3.17	3.17
T2	2024	13.30	28.33	177.33	88.33	3.33	3.33
T3	2023	12.60	30.17	179.67	87.17	3.67	3.67
T3	2024	12.80	31.00	182.33	98.33	4.00	4.00
T4	2023	14.00	34.17	186.83	90.50	4.00	4.00
T4	2024	14.33	35.00	187.33	110.33	4.33	4.33
T5	2023	15.30	38.17	207.00	94.50	4.33	4.33
T5	2024	15.60	39.00	207.33	124.33	4.67	4.67
T6	2023	16.00	42.33	227.83	97.17	4.67	4.67
T6	2024	16.50	43.33	229.00	136.33	5.00	5.00
T7	2023	17.10	52.50	259.17	102.50	5.83	5.83
T7	2024	17.57	53.67	261.67	156.33	6.33	6.33

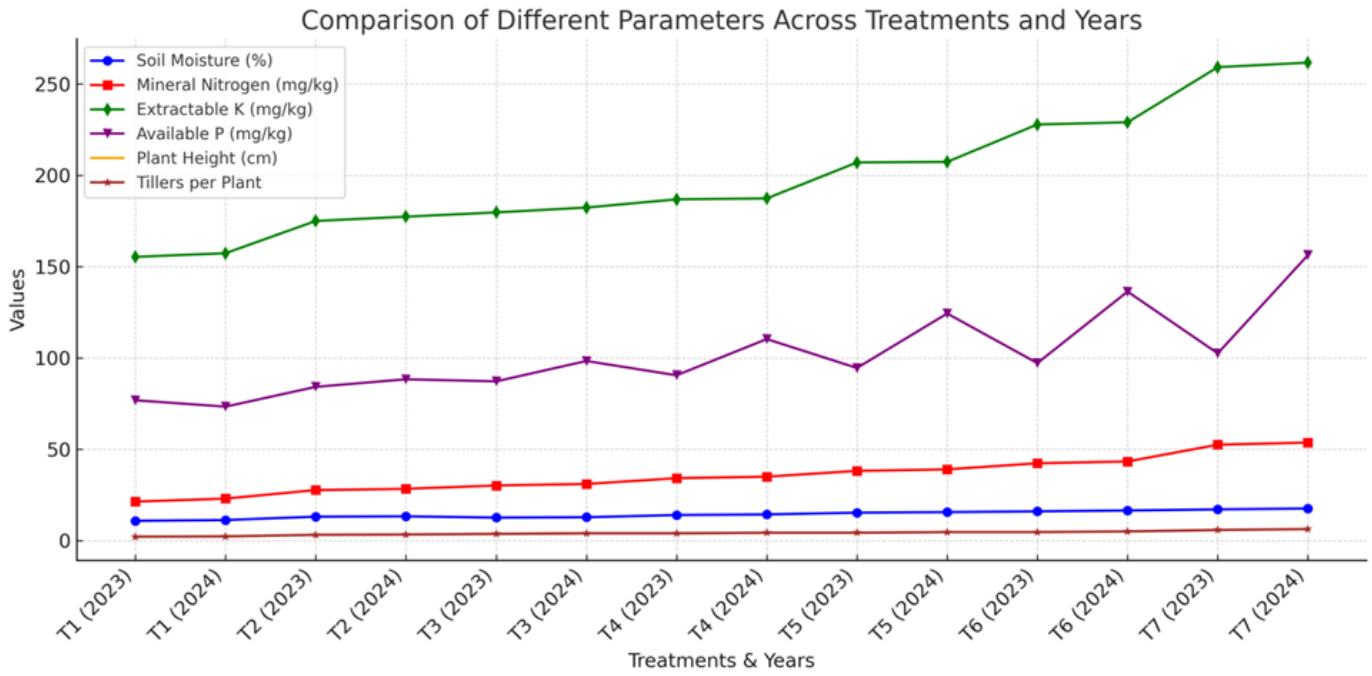

Figure 1. Comparison of different treatments and year across soil and plant growth parameters.

DISCUSSION

These experiments show that the combined use of mulch and bio-fertilizers greatly improved Italian ryegrass (*Lolium multiflorum*) soil quality, crop growth, forage yield, and seed output. These results correspond with earlier studies that have always emphasized the value of mulch and biofertilizers in increasing crop yields and soil quality, especially in semiarid areas (Tubeileh & Thomas, 2023; Naorem et al., 2023). The noted changes in soil moisture retention,

nutrient availability, and plant growth characteristics highlight the possibility of integrated nutrient management approaches to solve agricultural issues in water deprived conditions.

Table 2. Yield and quality parameters.

Treatment	Year	Fresh Biomass (kg/ha)	Dry Matter Yield (kg/m²)	Grain Yield (g/m²)	Crude Protein (%)	Crude Fiber (%)
T1	2023	3120.3	682.0	72.33	8.73	31.77
T1	2024	3177.3	715.3	73.33	8.90	31.27
T2	2023	3843.0	877.7	86.67	10.13	30.27
T2	2024	3923.0	896.3	88.33	10.33	30.00
T3	2023	4168.3	927.3	96.67	11.20	28.77
T3	2024	4171.0	963.3	98.33	11.33	28.80
T4	2023	4424.7	988.0	108.33	12.20	28.30
T4	2024	4518.7	1021.0	110.33	12.33	28.20
T5	2023	4723.0	1068.7	124.67	13.20	27.90
T5	2024	4794.3	1072.0	124.33	13.40	27.77
T6	2023	5125.7	1208.0	135.67	14.17	27.47
T6	2024	5268.3	1200.7	136.33	14.40	27.30
T7	2023	5671.0	1422.7	152.33	15.70	31.27
T7	2024	5706.7	1432.0	156.33	15.90	31.77

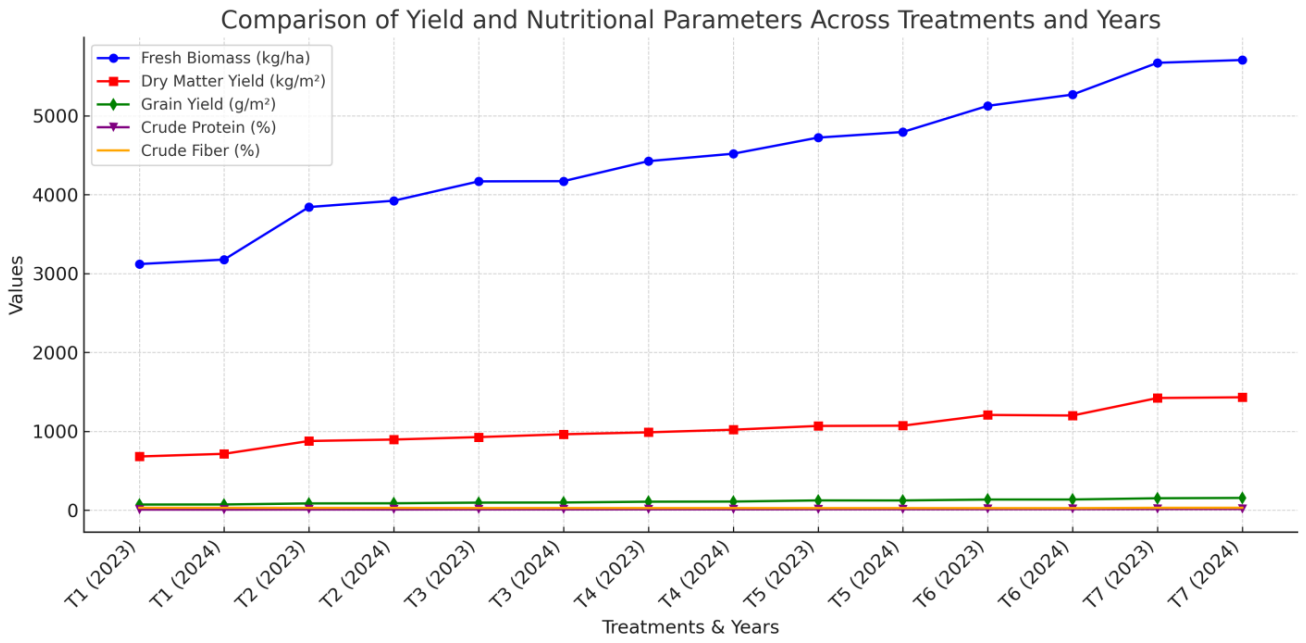

Figure 2. Comparison of yield and nutritional parameter across treatments and year.

Soil Nutrients Dynamics

Rahangdale et al. (2022) attribute the major rise in soil moisture under the combined application of mulch and bio-fertilizers (T7) to mulch's capacity to lower evaporation and bio-fertilizers' capacity to improve soil structure. Saputra et al. said comparable results were found. (2025) noted that mulch added water retention in semiarid soils, while bio-fertilizers encouraged microbial activity which in turn improved soil aggregation and water holding capability. Higher levels of mineral nitrogen, extractable potassium, and available phosphorus in T7 further support the part of bio-fertilizers in improving nutrient availability using nitrogen fixation, potassium solubilization, and phosphorus.

Plant Grow and Yield Characteristics

Table 3. Correlation analysis of soil and plant growth parameters.

Parameter	Soil Moisture (%)	Mineral N (mg/kg)	Extractable K (mg/kg)	Available P (mg/kg)	Plant Height (cm)	Tillers/Plant
Soil Moisture (%)	1.000	0.968	0.967	0.985	0.987	0.969
Mineral N (mg/kg)	0.968	1.000	0.992	0.992	0.979	0.986
Extractable K (mg/kg)	0.967	0.992	1.000	0.986	0.965	0.971
Available P (mg/kg)	0.985	0.992	0.986	1.000	0.989	0.978
Plant Height (cm)	0.987	0.979	0.965	0.989	1.000	0.989
Tillers/Plant	0.969	0.986	0.971	0.978	0.989	1.000

Correlation matrix showing the relationships between soil properties (soil moisture, mineral nitrogen, extractable potassium, and available phosphorus) and plant growth parameters (plant height and tillers per plant). Strong positive correlations indicate that improvements in soil properties enhance plant growth.

Table 4. Correlation analysis of yield and quality parameters.

Parameter	Fresh Biomass (kg/ha)	Dry Matter Yield (kg/m²)	Grain Yield (g/m²)	Crude Protein (%)	Crude Fiber (%)
Fresh Biomass (kg/ha)	1.000	0.981	0.991	0.995	-0.968
Dry Matter Yield (kg/m²)	0.981	1.000	0.979	0.978	-0.919
Grain Yield (g/m²)	0.991	0.979	1.000	0.999	-0.945
Crude Protein (%)	0.995	0.978	0.999	1.000	-0.960
Crude Fiber (%)	-0.968	-0.919	-0.945	-0.960	1.000

Correlation matrix showing the relationships between yield parameters (fresh biomass, dry matter yield, and grain yield) and quality parameters (crude protein and crude fiber). Positive correlations indicate that higher yields are associated with improved forage quality, while negative correlations with crude fiber suggest enhanced digestibility.

mineralization (Olaniyan et al., 2022). These findings are in line with previous research showing the synergistic impacts of inorganic and organic supplements on soil fertility and nutrient uptake (Liu et al., 2022). Higher in T7 were the height of the plant and the tiller count, therefore showing better nutrient availability and soil moisture retention. These results correspond with those of Sarkar et al., (2021), which found that integrated nutrient management methods improved forage crop vegetative growth by maximizing resource use efficiency. T7 had also the greatest fresh biomass yield and dry matter yield, in line with (Chaudhari et al., 2021) results discovered that using mulch and bio-fertilizers together improved soil quality and plant nutrient uptake, hence boosting forage output. The higher grain yield in T7 is much in line with (Boubaker et al., 2023) results as compared to the control which noted that by increasing nutrient availability and reproductive growth, bio-fertilizers boosted seed output.

Forage Quality

T7 showed much higher crude protein levels and lower crude fiber levels pointing at better forage quality. These findings align with those of (Karimi et al., 2025) reported that bio fertilizers allowed nitrogen assimilation in plants, which led to greater protein content. The decrease in crude fiber content points better digestibility, something vital for livestock nutrition (Akinbomi et al., 2025; Sajjad et al., 2023). (Chand et al, 2022) also found results close to those of this research, who noted that forage crops had their fiber content dropped and nutritional value raised by integrated nutrient management techniques.

Correlational Analysis

Strong positive links between soil moisture, nutrient availability, plant growth, and yield parameters serve to confirm more the integrated effects of mulch and bio-fertilizers. Earlier research in semiarid regions (Lotfollahi et al., 2023) emphasized the dependence of plant performance on soil characteristics. The negative correlation between crude fiber content and other parameters suggests that improved nutrient availability and plant growth reduce the proportion of structural carbohydrates, enhancing forage digestibility (Chand et al., 2022).

Comparison of Current Research to Earlier Findings

Several prior studies found results that match the ones of this research, while plant growth and yield in forage plants were improved by bio-fertilizers. Similarly, Yadav et. (2023) noted that by using integrated nutrient management techniques, forage quality improved as fiber content decreased and crude protein content grew. The present research adds to these results by showing the sustained advantages of integrated nutrient management in improving seed yield and forage in Italian ryegrass. To put it simply, the combined use of mulch and bio fertilizers greatly increased seed production, forage yield, plant growth, and soil quality for the Italian ryegrass. These results emphasize how integrated nutrient management approaches could improve forage quality and crop yields in semiarid areas. The findings support previous research and give a solid starting point for the creation of sustainable agriculture techniques that maximize potential yield and increase resource use efficiency. Further confirming these results and investigating the financial feasibility of integrated nutrient management techniques in several agro ecological zones would be the subject of long-term field studies in future research.

CONCLUSION

The research clearly shows that the combined use of mulch and bio-fertilizers greatly improves Italian ryegrass soil quality, plant growth, forage yield, and seed output. Consistently, the main result reveals that the combined treatment (T7: mulch + fertilizer + bio-fertilizer) outperforms all others by having the greatest soil moisture retention (17.33 percent), mineral nitrogen (52.50 mg/kg), extractable potassium (259.17 mg/kg), available phosphorus (102.50 mg/kg), plant height (5.83 cm), tiller number (6.33), fresh biomass yield (5688.8 kg/ha), dry matter yield (1427.3 kg/m²), grain yield (17.57 g/m²), and crude protein content (1.80%), while significantly decreasing crude fiber content (5.00%). These enhancements bring out the cooperating actions of mulch and bio-fertilizer in maximizing plant growth, nutrient availability, and soil moisture. Mainly, the point is that combining bio-fertilizers and mulch provides a sustainable, efficient method of enhancing forage and seed yield in Italian ryegrass, especially in semiarid areas. This method increases crude protein and lowers crude fiber, so besides boosting crop output it also improves forage quality, making it a practical answer for sustainable agriculture and livestock nutrition. Such results give a solid basis for the use of integrated nutrient management techniques to optimize agricultural output and resource use efficiency.

.

AUTHOR'S CONTRIBUTION

Hussain Ahmad: Conceptualization, experiment design, data analysis. Waleed Azhar: Conducted field experiment, data collection, and initial draft preparation. Zain ul Sajjad: Assisted in data analysis and manuscript writing. Syed Tanzeel Husnain: Statistical analysis and result interpretation. Syed Awais Hussain Shah: Contributed to experimental setup and field management. Khawar Abbas: Assisted in reviewing and editing the manuscript. Muhammad Owais Dogar: Helped in preparing tables, figures, and formatting. Zuhair Husnain: Supervision, Proofreading, corrections, and critical revision. Mahmood-ul-Hassan: Supervision, guidance, and final approval of the manuscript.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

AVAILABILITY OF DATA AND MATERIAL

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable. This research did not involve human participants or animals requiring ethical approval.

CONSENT FOR PUBLICATION

All authors have read and approved the final version of the manuscript and consent to its publication.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the Department of Agronomy, PMAS Arid Agriculture Rawalpindi, for providing experimental facilities and technical guidance.

REFERENCES

Akinbomi, J. G., Patinvoh, R. J., Atunrase, O. S., Onyenuwe, B. C., Emereonye, C. N., Ajeigbe, J. F., & Taherzadeh, M. J. (2025). Evaluating potentials of activated carbon, inoculum diversity, and total solids content for improved digestate quality in anaerobic food waste treatment. Processes, 13(2), 382.

Alharbi, S., Felemban, A., Abdelrahim, A., & Al-Dakhil, M. (2024). Agricultural and technology-based strategies to improve water-use efficiency in arid and semiarid areas. Water, 16(13), 1842.

Boubaker, H., Saadaoui, W., Dasgan, H. Y., Tarchoun, N., & Gruda, N. S. (2023). Enhancing seed potato production from in vitro plantlets and microtubers through biofertilizer application: Investigating effects on plant growth, tuber yield, size, and quality. Agronomy, 13(10), 2541.

Chand, S., Indu, Singhal, R. K., & Govindasamy, P. (2022). Agronomical and breeding approaches to improve the nutritional status of forage crops for better livestock productivity. Grass and Forage Science, 77(1), 11–32.

Chaudhari, S., Upadhyay, A., & Kulshreshtha, S. (2021). Influence of organic amendments on soil properties, microflora and plant growth. Sustainable Agriculture Reviews, 52, 147–191.

Devi, L., Sheikh, S., Kumari, N., & Kumar, R. (2022). Role of biofertilizers in organic agriculture. A Monthly Peer Reviewed Magazine for Agriculture and Allied Sciences, 1, 42–45.

El-Beltagi, H. S., Basit, A., Mohamed, H. I., Ali, I., Ullah, S., Kamel, E. A., & Ghazzawy, H. S. (2022). Mulching as a sustainable water and soil saving practice in agriculture: A review. Agronomy, 12(8), 1881.

García-Favre, J., Zanoniani, R., Lopez, I. F., Cadenazzi, M., Sacido, M., Mailhos, M. E., & Boggiano, P. (2021). Ecosystem and productive benefits of the strategic inclusion of annual legumes into an annual ryegrass pasture in a no-tillage integrated crop-livestock system. RIA. Revista de Investigaciones Agropecuarias, 47(3), 344–353.

Hussain, A., Elkarmout, A. F., Mansour, E. Z., Awais, M., Usman, M., Ahmad, H., & Ahmad, T. (2024). An environment friendly practice, the climate smart agriculture crop production and soil management systems: A review. Journal of Sustainable Agricultural and Environmental Sciences, 3(3), 101–124.

Imran, Amanullah, Ortas, I., Mahmood, T., Arif, M., Al-Tawaha, A. R. M. S., & Ilyas, M. (2022). Challenges of soil fertility under changing climate and its opposing components. In Climate Change and Agriculture: Perspectives, Sustainability and Resilience (pp. 157–178).

Janardhan, S., & Krishna, G. S. (2021). Role of biochar in agriculture—Its implications and perspectives. Agriculture & Food: E-Newsletter.

Karimi, M., Sayfzadeh, S., Pazoki, A., Hadidi Masouleh, E., & Zakerin, H. R. (2025). Effects of bio-fertilizers and nitrogen levels on yield and quality of single-cross maize (KSC 704). Journal of Plant Nutrition, 1–17.

Liu, M., Linna, C., Ma, S., Ma, Q., Song, W., Shen, M., & Wang, L. (2022). Biochar combined with organic and inorganic fertilizers promoted the rapeseed nutrient uptake and improved the purple soil quality. Frontiers in Nutrition, 9, 997151.

Lotfollahi, L., Delavar, M. A., Biswas, A., Jamshidi, M., Fatehi, S., & Taghizadeh-Mehrjardi, R. (2023). Spatial prediction and uncertainty estimation of crucial GlobalSoil Map properties—A contextual study in the semi-arid area of western Iran. Geoderma Regional, 35, e00713.

Mclennon, E., Dari, B., Jha, G., Sihi, D., & Kankarla, V. (2021). Regenerative agriculture and integrative permaculture for sustainable and technology driven global food production and security. Agronomy Journal, 113(6), 4541–4559.

Meddich, A., Oufdou, K., Boutasknit, A., Raklami, A., Tahiri, A., Ben-Laouane, R., & Baslam, M. (2020). Use of organic and biological fertilizers as strategies to improve crop biomass, yields and physicochemical parameters of soil. In Nutrient Dynamics for Sustainable Crop Production (pp. 247–288).

Murtaza, G., Ahmed, Z., Eldin, S. M., Ali, B., Bawazeer, S., Usman, M., & Tariq, A. (2023). Biochar-soil-plant interactions: A cross talk for sustainable agriculture under changing climate. Frontiers in Environmental Science, 11, 1059449.

Naorem, A., Jayaraman, S., Dang, Y. P., Dalal, R. C., Sinha, N. K., Rao, C. S., & Patra, A. K. (2023). Soil constraints in an arid environment—Challenges, prospects, and implications. Agronomy, 13(1), 220.

Nosheen, S., Ajmal, I., & Song, Y. (2021). Microbes as biofertilizers, a potential approach for sustainable crop production. Sustainability, 13(4), 1868.

Olaniyan, F. T., Alori, E. T., Adekiya, A. O., Ayorinde, B. B., Daramola, F. Y., Osemwegie, O. O., & Babalola, O. O. (2022). The use of soil microbial potassium solubilizes in potassium nutrient availability in soil and its dynamics. Annals of Microbiology, 72(1), 45.

Poudel, P., Ødegaard, J., Mo, S. J., Andresen, R. K., Tandberg, H. A., Cottis, T., & Solberg, S. Ø. (2022). Italian ryegrass, perennial ryegrass, and meadow fescue as undersown cover crops in spring wheat and barley: Results from a mixed methods study in Norway. Sustainability, 14(20), 13055.

Rahangdale, N., Kumawat, N., Jadav, M. L., Bhagat, D. V., Singh, M., & Yadav, R. K. (2022). Symbiotic efficiency, productivity and profitability of soybean as influenced by liquid bio-inoculants and straw mulch. International Journal of Bio-resource and Stress Management, 13(1), 9–16.

Ray, P. K., & Bharti, P. (2023). Biochar: A quality enhancer for fruit crops. In International Year of Millets (p. 77).

Rao, I., Peters, M., Castro, A., Schultze-Kraft, R., White, D., Fisher, M., ... & Rudel, T. (2015). LivestockPlus—the sustainable intensification of forage-based agricultural systems to improve livelihoods and ecosystem services in the tropics. *Tropical Grasslands-Forrajes Tropicales*, *3*(2), 59-82.

Sajjad, Z. ul, Zia, F., Aslam, M. U., Shafqat, M., Malook, M. B., Ali, H. R., Ahmad, M., & Inqalabi, T. E. I. (2024). Assessing the early establishment and adaptability of Italian ryegrass (Lolium multiflorum) in irrigated and rainfed conditions of Punjab, Pakistan. Asian Plant Research Journal, 12(5), 1–10. https://doi.org/10.9734/aprj/2024/v12i5266

Sajjad, Z. U., Fatima, Z., Awais, M., Waheed, A., Ali, A., Hashmi, Q. A., ... & Sufyan, A. (2023). Effect of Polyethylene Glycol (PEG) on Germination and Seedling Parameters of Maize Varieties. *Asian Journal of Research in Crop Science*, *8*(4), 410-420.

Saputra, H., Soleh, M. A., Hamdani, J. S., & Saryoko, A. (2025). The potential and differences between mulch and organic matter in reducing drought stress in plants–A review. Cogent Food & Agriculture, 11(1), 2454342.

Sarkar, D., Rakshit, A., Al-Turki, A. I., Sayyed, R. Z., & Datta, R. (2021). Connecting bio-priming approach with integrated nutrient management for improved nutrient use efficiency in crop species. Agriculture, 11(4), 372.

Shilomboleni, H., Recha, J., Radeny, M., & Osumba, J. (2023). Scaling climate resilient seed systems through SMEs in Eastern and Southern Africa: Challenges and opportunities. Climate and Development, 15(3), 177–187.

Tubeileh, A. M., & Thomas, R. J. (2023). The management of soil systems in arid and semi-arid climates. In Biological Approaches to Regenerative Soil Systems (pp. 55–66). CRC Press.

Vanvanhossou, S. F. U., Dossa, L. H., & König, S. (2021). Sustainable management of animal genetic resources to improve low-input livestock production: Insights into local Beninese cattle populations. Sustainability, 13(17), 9874.

Wang, B., Niu, J., Berndtsson, R., Zhang, L., Chen, X., Li, X., & Zhu, Z. (2021). Efficient organic mulch thickness for soil and water conservation in urban areas. Scientific Reports, 11(1), 6259.

Xie, Y., Liu, X., Amee, M., Yu, H., Huang, Y., Li, X., & Sun, X. (2021). Evaluation of salt tolerance in Italian ryegrass at different developmental stages. Agronomy, 11(8), 1487.

Yadav, M. R., Singh, M., Kumar, R., Kumar, D., Ram, H., Meena, R. K., & Makarana, G. (2023). Productivity, quality, and land use efficiency of cereal-legume forages under mono-cropping and intercropping systems with integrated use of organic and inorganic nutrient sources. Journal of Plant Nutrition, 46(10), 2231–2245.

Young, M. D., Ros, G. H., & de Vries, W. (2021). Impacts of agronomic measures on crop, soil, and environmental indicators: A review and synthesis of meta-analysis. Agriculture, Ecosystems & Environment, 319, 107551.