



Farmyard Manure as K-Fertilizer Modulates Soil Biological Activities and Yield of Wheat Using the Integrated Fertilization Approach

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Potassium fertilization is often ignored by assuming alluvial soils have sufficient K reserves in the North West Plain Zone of India under cereal-based cropping systems. There is scanty information on the impact of integrated K fertilization on soil enzymes, nutrients availability, microbial population, and wheat yield cultivated in the corn-wheat cropping system. The current study exhibits that treatment (T₇) applied with a dose of 90 kg K ha⁻¹ [30 kg K by farmyard manure (FYM) and 60 kg K by muriate of potash (MOP)] significantly enhances the various microbial populations from 48.00 to 123.10% and 39.00 to 124.00%, soil enzymatic activities from 70.31 to 180.00% and 102.42 to 175.68%, and available nutrients from 2.43 to 8.44% and 14.79 to 22.87% for the first and second years of wheat cultivation, respectively. It also improved various yield parameters (12.39–41.71% and 18.24–41.14%) during both the consecutive years of cultivation. Statistical analyses revealed that the treatments (T₄, T₅, and T₇) applied with integrated fertilization of wheat cultivation through FYM and MOP were more promising for improving soil enzymatic activities (11.59–57.22%), microbial populations (5.14–15.70%), available nutrients in soil (7.60–16.54%), and crop yield (1.06–5.85%) during the second year of cultivation as compared to the first year of cultivation. This study might be helpful to reclaim soil health and reduce chemical fertilizers used in agricultural lands.

Keywords: farmyard manure, functional activities, microbial population count, soil enzymatic activities, integrated fertilization approach, yield, wheat

INTRODUCTION

Soil is home to different kinds of microbes and enzymes. The activities and functions of these microbes and soil enzymes are dependent on soil pH, soil temperature, soil organic matter, cropping system, crop management factors, soil amendments, and conditioners. Soil microbial population and enzymatic activities are a key driving force that helps in degeneration and management of exogenic plant material and anthropogenic depositions, conversion of organic matter, and progression and conservation of the soil structure (Canarutto et al., 1995; Bandick and Dick, 1999). The function of the secondary trophic levels mainly relies on the energy prevalent through primary organic matter

decomposer soils. Subsequently, this functional process contributes a significant role in the cycling of nutrients and favor to plant life (Clarholm and Rosengren-Brinck, 1995; Balota et al., 2003). The enzymatic activities and soil microbial populations preserve soil health and fertility by imparting alterations through their biochemical procedures (Nannipieri et al., 2003; Okore et al., 2012).

In India, post green revolution, intensive agriculture replaced subsistence farming. New cropping systems and farming systems were tested and have evolved across the country. In these cropping systems, rice–wheat systems and corn–wheat systems occupy a major part. Wheat is generally cultivated in the winter season due to its climatic requirements. Wheat is the essential cereal crop that fulfils the feed, food, fodder, and industrial needs globally. It is often cultivated in the alluvial soils of northwestern India (Luan et al., 2016). The corn–wheat cropping is extremely rigorous concerning about the removal of nutrients from the soil.

Under an intensive cropping system, farmers are utilizing especially nitrogen (N) and phosphorus (P) fertilizer in an uncontrolled and imbalanced manner, which results in creating a negative potassium (K) nutrient balance in the soil. High removal of K by the crop compared to the amount of K applied in the soil by farmers, and an imbalanced application of the NPK fertilizer leads to a huge amount of K excavation and insufficiency in soils and crops (Yousaf et al., 2017; Li et al., 2019). The input–output proportions of K in India showed negative K proportions (in 10,000 tonnes) among most of the states such as Haryana (–346), Uttar Pradesh (–931), and Punjab (–577). They also reported that less application of K contributes to nutrient excavation from the soil, which leads to depletion of soil fertility and may significantly limit crop yields in the future (Dutta et al., 2013; Dwevedi et al., 2017; Rajawat et al., 2020). Farmyard manure (FYM) is a decomposed mixture of dung, urine, litter, and leftover materials from roughages and fodder fed to animals. A well-decomposed FYM contains 0.5–1.5% N, 0.2–0.4% P₂O₅, and 0.5–1.0% K₂O. FYM is a good source of organic carbon, which activates the biotic life of the soil flora and fauna. Ghoshal and Singh (1995) found an increase in soil microbial biomass carbon, nitrogen, and phosphorous in the soil applied with FYM. Using long-term experiments, Kaur and Benipal (2006) reported an increase in different forms of K when FYM was applied in the soil. A study was carried out by collecting surface soil (depth 0–15 cm) and foliar samples of various crops such as cotton, sugarcane, wheat, and rice crops intensively grown by farmers in the fields of India during 2004 and 2005 and reported widespread deficiency K in the soils and crops (Singh and Bansal, 2009). Similarly, based on the Soil Health Card database derived from eight districts of different agroclimatic zones of India, most of the districts' average plant-available K status (kg K₂O ha^{–1}) was medium to low in their K status (Patra et al., 2017).

Potassium is the most crucial macronutrient for plant development and crop yield. Many crops take up a substantial quantity of K through their roots from the soil (Steingrobe and Claassen, 2000). Potassium contributes a vital role for antagonistic and synergistic interactions with other nutrients (Dibb and Thompson, 1985). Potassium amends root development, increases tolerance to drought, increases nutrient assimilation and translocation, produces starch and protein–enriched grain, and

decreases crop lodging and diseases (Dobermann, 2001; Polara et al., 2009; Nejad et al., 2010).

The current study was carried out to understand the influence of integrated K fertilization through FYM and muriate of potash (MOP) on soil microbial populations (bacterial population, K-solubilizing bacteria, P-solubilizing bacteria, actinomycetes, and cellulose-degrading bacteria), soil enzyme activities (dehydrogenase, fluorescein diacetate (FDA), β-glucosidase, and acid and alkaline phosphatase), available nutrients (nitrogen, phosphorus, and potassium), and yield parameters of wheat crop (grain, straw, and biological) in farm field condition under the corn–wheat cropping system. This study might be beneficial to contribute to soil reclamation and improve crop productivity with low input cost value for sustainable agriculture.

MATERIALS AND METHODS

Experimental Site

The field trials were performed in wheat during the winter season and in corn during the rainy season in the first and second years at the farm field of ICAR-Indian Agricultural Research Institute, New Delhi (India) (28.35 N, 77.12 E). During the cultivation period in the first and second years of corn cultivation, the maximum and minimum temperatures ranged between 38.5°C and 19.8°C, and 38.2°C and 22.0°C, respectively. In the first year, the daily maximum and minimum temperatures during the period of wheat cultivation were 35.4°C and 2.0°C, whereas in the second year, these were 0 and 39.0°C, respectively. The wheat crop encountered 65.6 mm of rainfall, having 11 rainy days in the first year, and 40.8 mm of rainfall, having 4 rainy days in the second year.

The soils from experimental fields were characterized as sandy loam, and the characteristics are as follows: EC, 0.43 ± 0.02 dS m^{–1}; pH, 8.0 ± 0.2; available N, 173.30 ± 8.45 kg ha^{–1}; available K, 261.00 ± 12.40 kg ha^{–1}; organic carbon, 0.40 ± 0.03% (w/w); and available P, 13.80 ± 0.72 kg ha^{–1}. The field study was performed at fixed sites in a randomized block design in triplicates and seven treatments. Different treatments designed for corn (C) during the rainy season and wheat (W) during the winter season are given in **Table 1**. Recommended doses of nitrogen (120 kg N ha^{–1}) and phosphorus (26 kg P ha^{–1}) were used for wheat by introducing chemical fertilizers—urea and diammonium phosphate, respectively. The full dose of potassium (K) and phosphorus (P) was employed as basal, whereas nitrogen (50 kg N ha^{–1}) was employed as basal, and the rest 100 kg N ha^{–1} was employed in equal split doses after 30 and 60 days of sowing (Nejad et al., 2010). FYM and MOP were employed as the sources of K. The recommended dose for wheat was applied—120 kg N ha^{–1} and 26 kg P ha^{–1} through urea and diammonium phosphate (DAP), respectively. FYM was examined for N, P, and K content that showed 5.46 ± 0.13 g N kg^{–1}, 4.32 ± 0.09 g P kg^{–1}, and 5.51 ± 0.17 g K kg^{–1} for the first year and 6.34 ± 0.17 g N kg^{–1}, 4.23 ± 0.07 g P kg^{–1}, and 4.43 ± 0.11 g K kg^{–1} for the second year in field, respectively, where FYM was applied as a source of fertilizer. The quantity of N, P, and K employed by urea, DAP, and FYM was maintained among treatments for maintaining the recommended doses of N, P, and K according to the designed experiments. The final quantity of N, P, and K was introduced in the field during corn and

TABLE 1 | Experimental design of different treatments using FYM for integrated potassium fertilization under the corn–wheat cropping system.

Symbol	Details of treatment	Crop	Amount of nutrient applied (kg/ha)		
			N	P	K
T ₁	K ₀ (C)–K ₀ (W)	Corn (C)	150	26	0
		Wheat (W)	120	26	0
T ₂	MOP ₃₀ + FYM ₃₀ (C)–MOP ₆₀ (W)	Corn (C)	150	26	60
		Wheat (W)	120	26	60
T ₃	MOP ₆₀ + FYM ₃₀ (C)–K ₀ (W)	Corn (C)	150	26	90
		Wheat (W)	120	26	0
T ₄	K ₀ (C)–MOP ₃₀ + FYM ₃₀ (W)	Corn (C)	150	26	0
		Wheat (W)	120	26	60
T ₅	MOP ₆₀ (C)–MOP ₃₀ + FYM ₃₀ (W)	Corn (C)	150	26	60
		Wheat (W)	120	26	60
T ₆	MOP ₆₀ (C)–MOP ₆₀ (W)	Corn (C)	150	26	60
		Wheat (W)	120	26	60
T ₇	K ₀ (C)–MOP ₆₀ + FYM ₃₀ (W)	Corn (C)	150	26	0
		Wheat (W)	120	26	90

wheat crop cultivation, as mentioned in **Table 1**. The corn hybrid variety “PEHM2” (CM137 × CM138) was selected for the present study and sown with a seed rate of 20 kg seed ha⁻¹ and spacing at 60 × 20 cm maintained. The wheat variety “HD 2967” was used in this study with a seed rate of 100 kg seed per hectare and maintained the spacing at 22.50 × 5.00 cm. The wheat variety “HD 2967” tolerant to rust, with a moderate level of tolerance to the Ug₉₉ race of stem rust, was used for the present study.

Estimation of Effect of Integrated Fertilization on Soil Parameters

Analysis of Microbial Population Count

The soil samples were collected from the rhizospheric regions of the root at crop maturity to examine the influence of integrated potassium application on microbial populations and enzymatic activities. The microbial population count was performed through serial dilution followed by spreading on respective agar plates. We analyzed the total bacterial population, P-solubilizing bacteria, actinomycetes, K-solubilizing bacteria, and cellulose-degrading bacteria using nutrient agar, Pikovskaya agar, Kenknight and Munaier’s agar, Aleksandrov medium, and carboxymethyl cellulose agar media, respectively.

Analysis of Soil Enzymatic Activities

FDA and dehydrogenase activities were performed by following the method of Green et al. (2006) and Klein et al. (1971), respectively. We analyzed the alkaline and acid phosphatase activities using the standard spectrophotometric method (Tabatabai and Bremner, 1969). The β-glucosidase activity was analyzed using the standard spectrophotometric method (Eivazi and Tabatabai, 1988).

Analysis of Available Nutrients

Soil samples were collected from each plot of the experimental field, mixed, air dried, sieved, and analyzed for the amount of available N using the alkaline KMnO₄ method (Subbaiah, 1956), 0.5 N sodium-bicarbonate-extractable P (Olsen, 1954), and 1.0 N Ammonium Acetate-extractable K (Jackson, 1973).

Estimation of Effect of Integrated Fertilization on Yield of Wheat

Wheat harvesting was done manually in an area of 4.5 m² from the center point of each plot. The dry weight of grains and stems was calculated individually. The straw and grain yield were analyzed by calculating the weight of the dried plant and further converted into tons per hectare.

Estimation of Cumulative Response of Integrated K Fertilization

The cumulative response of integrated K fertilization on soil health and wheat yield was estimated by the analysis of interactions among the various parameters (microbial population count, soil enzymatic activities, nutrients availability, and yield of wheat) and treatments studied. The statistical analysis was carried out using the data for each year separately and also analyzing the overall effect of integrated K-fertilization by using the data of both years of wheat cultivation.

Statistical Analysis

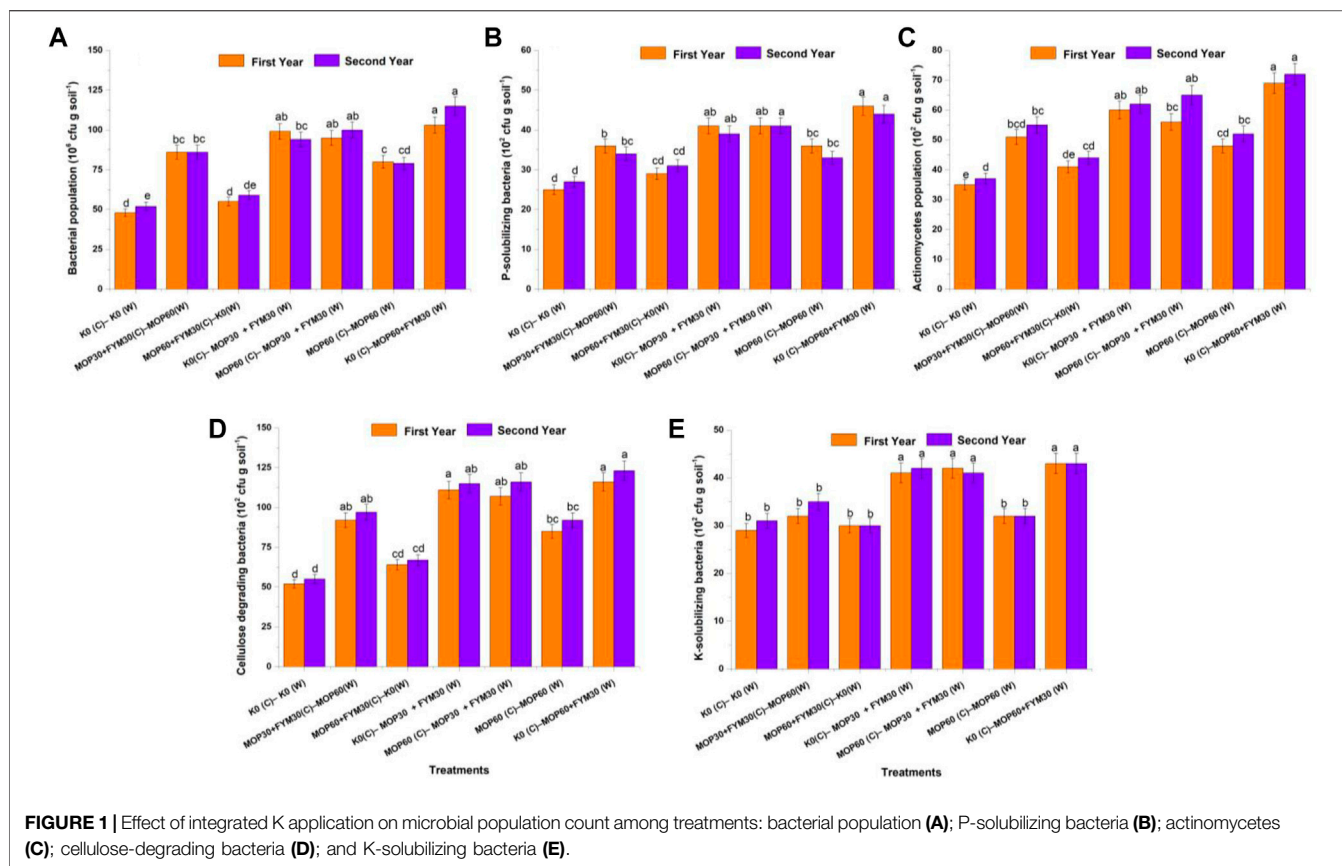
The obtained results were analyzed by employing the analysis of variance (ANOVA) technique for randomized block design (Gomez and Gomez, 1984). The least significant difference among the triplicates at $p \leq 0.05$ probability was calculated and shown as error bars. The principal component analysis and scatter plot matrix were performed through Origin Pro 9.0 software, OriginLab Corporation, United States. The heat map for the expression of various activities among treatments was prepared through Graphpad Prism 7.0 software, San Diego, California.

RESULTS

Microbial Population Count

Bacterial Population

The maximum bacterial population count was recorded as 1.03×10^8 and 1.15×10^8 cfu g soil⁻¹ in treatment T₇ during the first and second years of cultivation, respectively. Treatments T₄



(0.99×10^8 cfu g soil⁻¹) and T₅ (0.95×10^6 cfu g soil⁻¹) were recorded on a par with each other and had a higher bacterial population count than the other treatments during the first year of cultivation. Treatment T₁ was recorded the least for the bacterial population count in the first (0.48×10^8 cfu g soil⁻¹) and second (0.52×10^8 cfu g soil⁻¹) years of cultivation; while in the second year of cultivation, treatment T₅ was recorded as the second most promising treatment for the bacterial population count (1.0×10^8 cfu g soil⁻¹), followed by T₄ (0.94×10^8 cfu g soil⁻¹), T₂ (0.86×10^8 cfu g soil⁻¹), and T₆ (0.79×10^8 cfu g soil⁻¹). In this study, the bacterial population count was significantly improved through integrated fertilization of K in the combination of MOP and FYM among the treatments T₄ (106.25 and 80.80%), T₅ (97.92 and 92.30%), and T₇ (114.58 and 121.20%) as compared to treatment T₁ during the first and second years of wheat cultivation, respectively (Figure 1A).

P-Solubilizing Bacteria

The population of P-solubilizing bacteria was recorded as the highest (0.46×10^4 and 0.44×10^4 cfu g soil⁻¹) in treatment T₇ during the first and second years of cultivation, respectively; while treatments T₄ (0.41×10^4 and 0.39×10^4 cfu g soil⁻¹) and T₅ (0.41×10^4 and 0.41×10^4 cfu g soil⁻¹) were recorded on a par with each other during the first and second years of cultivation and improved the colonization of P-solubilizing bacteria in rhizospheric soil in comparison to other treatments, respectively. The least P-solubilizing bacterial count was

recorded in treatment T₁ during the first (0.25×10^4 cfu g soil⁻¹) and second (0.27×10^4 cfu g soil⁻¹) years of cultivation. Treatments T₄ (0.41×10^4 and 0.39×10^4 cfu g soil⁻¹) and T₅ (0.41×10^4 and 0.41×10^4 cfu g soil⁻¹) were jointly the second most effective treatment for improving P-solubilizing bacterial count followed by T₆ (0.36×10^4 and 0.33×10^4 cfu g soil⁻¹) and T₂ (0.36×10^4 and 0.34×10^4 cfu g soil⁻¹) during both the years of wheat cultivation, respectively. In this study, the P-solubilizing bacterial count was significantly improved through integrated fertilization of K in the combination of MOP and FYM among treatments T₄ (64.00 and 44.00%), T₅ (64.00 and 52.00%), and T₇ (84.00 and 63.00%) as compared to treatment T₁ during the first and second years of wheat cultivation, respectively (Figure 1B).

Actinomycetes

The population count of actinomycetes was recorded maximum (0.69×10^4 and 0.72×10^4 cfu g soil⁻¹) in treatment T₇ during the first and second years of cultivation, respectively. In the first year of wheat cultivation, treatment T₄ (0.60×10^4 cfu g soil⁻¹) was recorded as the second most effective as compared to T₁ (0.60×10^4 cfu g soil⁻¹), followed by T₅ (0.56×10^4 cfu g soil⁻¹), T₂ (0.51×10^4 cfu g soil⁻¹), and T₆ (0.48×10^4 cfu g soil⁻¹); while in the second year of cultivation, treatments T₄ (0.62×10^4 cfu g soil⁻¹) and T₅ (0.65×10^4 cfu g soil⁻¹) were recorded on a par with each other and had no significant differences. The least actinomycetes population was recorded in treatment T₁

(0.35×10^4 and 0.37×10^4 cfu g soil⁻¹) in the first and second years of cultivation, respectively. In this study, the population count of actinomycetes was significantly improved through integrated fertilization of K in the combination of MOP and FYM among the treatments T₄ (71.43 and 67.60%), T₅ (60.0 and 75.70%), and T₇ (97.14 and 94.60%) as compared to treatment T₁ during the first and second years of wheat cultivation, respectively (Figure 1C).

Cellulose-Degrading Bacteria

In the first year of wheat cultivation, the population of cellulose-degrading bacteria was recorded the maximum in treatment T₇ (1.16×10^4 cfu g soil⁻¹) and T₄ (1.11×10^4 cfu g soil⁻¹) followed by T₅ (1.07×10^4 cfu g soil⁻¹), T₂ (0.92×10^4 cfu g soil⁻¹), and T₆ (0.85×10^4 cfu g soil⁻¹); while during the second year of cultivation, treatment T₇ was recorded as the maximum population of cellulose-degrading bacteria (1.23×10^4 cfu g soil⁻¹). The population of cellulose-degrading bacteria in treatments T₄ (1.15×10^4 cfu g soil⁻¹) and T₅ (1.16×10^4 cfu g soil⁻¹) was on a par with each other. The least population of cellulose-degrading bacteria was recorded in treatment T₁ (0.52×10^4 and 0.55×10^4 cfu g soil⁻¹, respectively) during the first and second years of wheat cultivation. In this study, the population count of cellulose-degrading bacteria was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T₄ (113.50 and 109.10%), T₅ (105.80 and 110.90%), and T₇ (123.10 and 123.60%) as compared to treatment T₁ during the first and second years of wheat cultivation, respectively (Figure 1D).

K-Solubilizing Bacteria

The highest population of K-solubilizing bacteria was recorded in treatments T₇ (0.43×10^4 cfu g soil⁻¹ for each), T₄ (0.41×10^4 and 0.42×10^4 cfu g soil⁻¹), and T₅ (0.42×10^4 and 0.41×10^4 cfu g soil⁻¹) during the first and second years of wheat cultivation, respectively. The least population of K-solubilizing bacteria was recorded in treatments T₁ (0.29×10^4 cfu g soil⁻¹) and T₃ (0.30×10^4 cfu g soil⁻¹) during the first and second years of cultivation, respectively. In this study, the population count of K-solubilizing bacteria was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T₄ (41 and 35%), T₅ (45 and 32%), and T₇ (48 and 39%) as compared to treatment T₁ during the first and second years of wheat cultivation, respectively (Figure 1E).

Soil Enzymatic Activities

Soil Dehydrogenase

The soil dehydrogenase activity was recorded the maximum in treatment T₇ (142.0 ± 7.1 and 167.0 ± 8.35 µg TPF g soil⁻¹ d⁻¹), followed by T₄ (128.0 ± 6.4 and 152.0 ± 7.6 µg TPF g soil⁻¹ d⁻¹) and T₅ (129.0 ± 6.45 and 152.0 ± 7.6 µg TPF g soil⁻¹ d⁻¹) during the first and second years of cultivation, respectively. The least dehydrogenase activity was recorded in treatments T₁ (65.0 ± 3.25 and 72.0 ± 3.6 µg TPF g soil⁻¹ d⁻¹) and T₃ (75.0 ± 3.75 and 83.0 ± 4.15 µg TPF g soil⁻¹ d⁻¹) during the first and second years of

cultivation, respectively. In this study, dehydrogenase activity was significantly improved through integrated fertilization of K in the combination of MOP and FYM among treatments T₄ (96.92 and 111.11%), T₅ (98.46 and 111.11%), and T₇ (118.46 and 131.94%) as compared to treatment T₁ during the first and second years of cultivation, respectively (Figure 2A).

FDA

The soil FDA activity was recorded the maximum in treatment T₇ (9.5 ± 0.48 µg fluorescein g soil⁻¹ h⁻¹) followed by T₄ (7.4 ± 0.37 µg fluorescein g soil⁻¹ h⁻¹), T₅ (7.3 ± 0.36 µg fluorescein g soil⁻¹ h⁻¹), and T₂ (6.6 ± 0.33 µg fluorescein g soil⁻¹ h⁻¹) during the first year of wheat cultivation. Treatment T₇ (9.6 ± 0.48 µg fluorescein g soil⁻¹ h⁻¹), T₅ (9.4 ± 0.47 µg fluorescein g soil⁻¹ h⁻¹), and T₄ (9.3 ± 0.46 µg fluorescein g soil⁻¹ h⁻¹) were recorded for the maximum FDA activity during the second year of wheat cultivation. In this study, the FDA activity was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T₄ (100.00 and 132.50%), T₅ (97.30 and 135.00%), and T₇ (156.76 and 140.00%) as compared to treatment T₁ during the first and second years of cultivation, respectively (Figure 2B).

β-Glucosidase

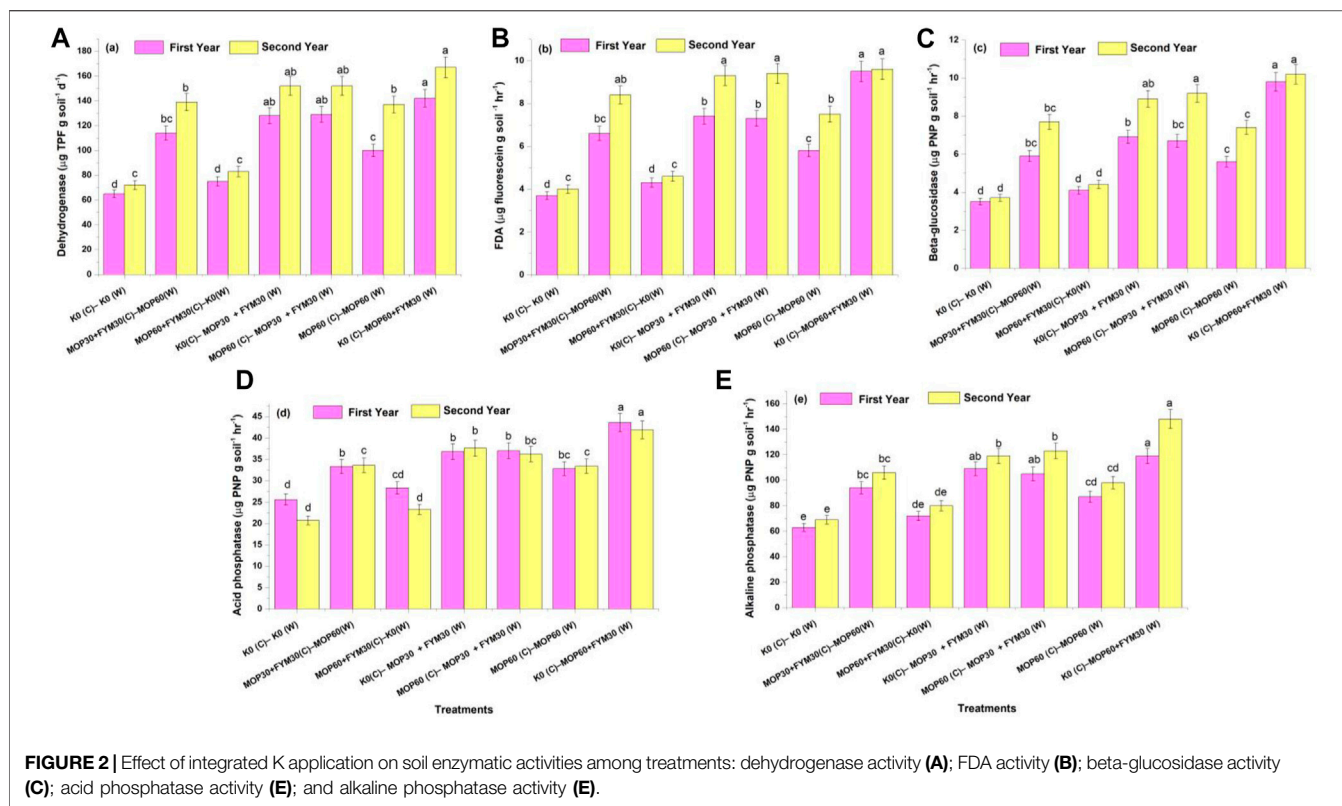
The β-glucosidase activity was recorded the maximum in treatment T₇ (9.8 ± 0.49 and 10.2 ± 0.51 µg PNP g soil⁻¹ h⁻¹), followed by T₅ (6.7 ± 0.34 and 9.2 ± 0.46 µg PNP g soil⁻¹ h⁻¹), T₄ (6.9 ± 0.35 and 8.9 ± 0.45 µg PNP g soil⁻¹ h⁻¹), and T₂ (5.9 ± 0.30 and 7.7 ± 0.39 µg PNP g soil⁻¹ h⁻¹) during the first and second years of wheat cultivation, respectively. In this study, the β-glucosidase activity was significantly increased through integrated fertilization of K in the combination of MOP and FYM among the treatments T₄ (97.14 and 140.54%), T₅ (91.43 and 148.65%), and T₇ (180.00 and 175.68%) as compared to treatment T₁ during the first and second years of cultivation, respectively (Figure 2C).

Acid Phosphatase

The acid phosphatase activity was recorded the maximum in treatment T₇ (43.6 ± 2.18 and 41.9 ± 2.10 µg PNP g soil⁻¹ h⁻¹), followed by T₄ (36.8 ± 1.84 and 37.6 ± 1.88 µg PNP g soil⁻¹ h⁻¹), T₅ (37.0 ± 1.85 and 36.2 ± 1.81 µg PNP g soil⁻¹ h⁻¹), T₂ (33.3 ± 1.68 and 33.6 ± 1.66 µg PNP g soil⁻¹ h⁻¹), and T₆ (32.8 ± 1.67 and 33.4 ± 1.64 µg PNP g soil⁻¹ h⁻¹) during the first and second years of wheat cultivation, respectively. The ANOVA showed that the acid phosphatase activity was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T₄ (43.75 and 81.64%), T₅ (44.53 and 74.88%), and T₇ (70.31 and 102.42%) as compared to treatment T₁ during the first and second years of cultivation, respectively (Figure 2D).

Alkaline Phosphatase

The alkaline phosphatase activity was recorded the maximum in treatment T₇ (119.0 ± 5.95 and 148.0 ± 7.40 µg PNP g soil⁻¹ h⁻¹), followed by T₅ (105.0 ± 5.25 and 123.0 ± 6.15 µg PNP g soil⁻¹ h⁻¹), T₄ (109.0 ± 5.45 and



$119.0 \pm 5.95 \mu\text{g PNP g soil}^{-1} \text{ h}^{-1}$), T_2 (94.0 ± 4.7 and $106.0 \pm 5.3 \mu\text{g PNP g soil}^{-1} \text{ h}^{-1}$), and T_6 (87.0 ± 4.35 and $98.0 \pm 4.9 \mu\text{g PNP g soil}^{-1} \text{ h}^{-1}$) during the first and second years of wheat cultivation, respectively. In this study, the alkaline phosphatase activity was significantly increased through integrated fertilization of K in the combination of MOP and FYM among the treatments T_4 (73.02 and 72.46%), T_5 (66.67 and 78.26%), and T_7 (88.89 and 114.49%) as compared to treatment T_1 during the first and second years of cultivation, respectively (Figure 2E).

Nutrients Availability in Soil

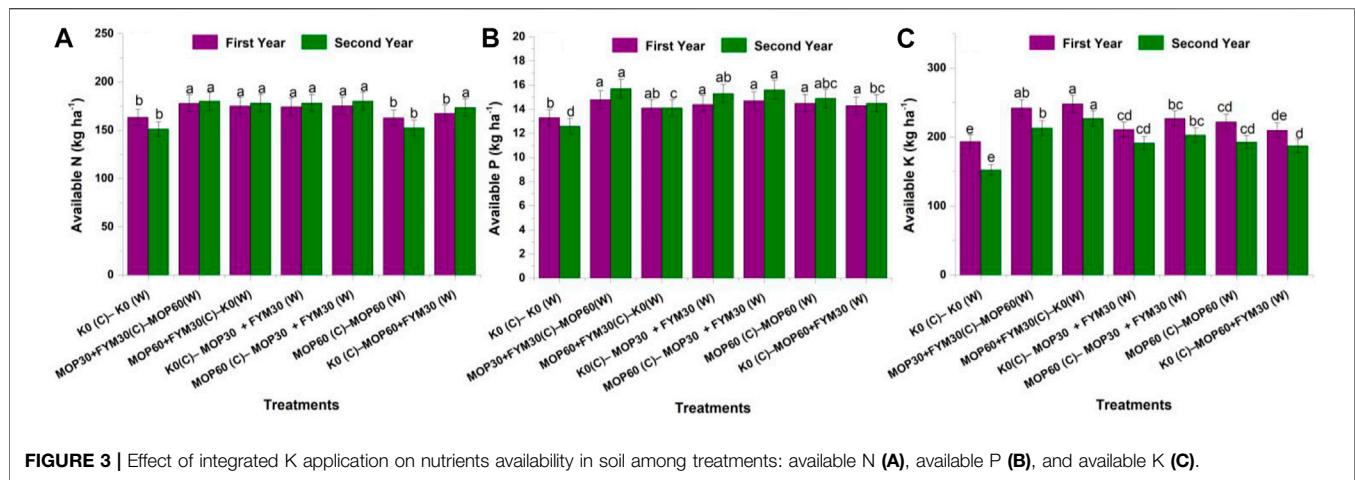
Available Nitrogen

During the first year of wheat cultivation, the availability of nitrogen through integrated fertilization of K among treatments T_2 ($177.90 \pm 8.90 \text{ kg N ha}^{-1}$), T_3 ($175.20 \pm 8.76 \text{ kg N ha}^{-1}$), T_4 ($174.30 \pm 8.72 \text{ kg N ha}^{-1}$), and T_5 ($175.40 \pm 8.877 \text{ kg N ha}^{-1}$) was recorded higher than treatment T_1 ($163.50 \pm 8.18 \text{ kg N ha}^{-1}$) and had no significant differences with each other. But, treatment T_7 ($167.50 \pm 8.38 \text{ kg N ha}^{-1}$) had no significant increment of available N compared to treatment T_1 . During the second year of wheat cultivation, a similar trend for enhancement of available N was recorded among the treatments and enhanced availability of N in treatment T_7 ($173.60 \pm 8.68 \text{ kg N ha}^{-1}$) compared to T_1 ($151.20 \pm 7.56 \text{ kg N ha}^{-1}$). In this study, we observed that the enhancement of available N was significantly higher during the second year of cultivation than in the first year of cultivation. The amount of available nitrogen declined

in the second year compared to the first year of wheat cultivation. In this study, available N was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T_4 (6.60 and 17.79%), T_5 (7.24 and 19.20%), and T_7 (2.43 and 14.79%) as compared to treatment T_1 during the first and second years of cultivation, respectively (Figure 3A).

Available Phosphorus

The amount of available P in soil was recorded the maximum in treatment T_2 ($14.80 \pm 0.74 \text{ kg P ha}^{-1}$), followed by treatment T_5 ($14.70 \pm 0.73 \text{ kg P ha}^{-1}$), T_4 ($14.40 \pm 0.72 \text{ kg P ha}^{-1}$), T_6 ($14.50 \pm 0.72 \text{ kg P ha}^{-1}$), and T_7 ($14.30 \pm 0.71 \text{ kg P ha}^{-1}$) during the first year of wheat cultivation. But there was no significance with each other. Integrated fertilization in the combination of MOP and FYM (T_4 , T_5 , and T_7) showed a significant difference compared to treatment T_1 ($13.30 \pm 0.67 \text{ kg P ha}^{-1}$). Besides, during the second year of wheat cultivation, the highest amount of available phosphorus was recorded in treatment T_2 ($15.70 \pm 0.78 \text{ kg P ha}^{-1}$), followed by treatments T_5 ($15.60 \pm 0.78 \text{ kg P ha}^{-1}$), T_4 ($15.30 \pm 0.76 \text{ kg P ha}^{-1}$), T_6 ($14.90 \pm 0.74 \text{ kg P ha}^{-1}$), and T_7 ($14.50 \pm 0.72 \text{ kg P ha}^{-1}$). In the current study, the amount of available phosphorus declined in the second year compared to the first year of wheat cultivation. But we observed that the enhancement of available phosphorus was significantly higher during the second year of cultivation than in the first year of cultivation. In this study, available phosphorus was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T_4 (8.79



and 21.75%), T_5 (10.80 and 23.87%), and T_7 (7.79 and 15.38%) as compared to treatment T_1 during the first and second years of cultivation, respectively (Figure 3B).

Available Potassium

Available K in soil was recorded the maximum in treatment T_3 ($248.30 \pm 12.42 \text{ kg K ha}^{-1}$), followed by treatment T_2 ($242.30 \pm 12.12 \text{ kg K ha}^{-1}$), T_5 ($227.10 \pm 11.36 \text{ kg K ha}^{-1}$), T_6 ($222.00 \pm 11.10 \text{ kg K ha}^{-1}$), and T_7 ($210.00 \pm 10.50 \text{ kg K ha}^{-1}$) during the first year of wheat cultivation. During the second year of wheat cultivation, the available K was recorded significantly the highest in treatment T_3 ($227.00 \pm 11.35 \text{ kg K ha}^{-1}$), followed by treatment T_2 ($213.00 \pm 10.65 \text{ kg K ha}^{-1}$), T_5 ($202.90 \pm 10.15 \text{ kg K ha}^{-1}$), and T_4 ($191.40 \pm 9.57 \text{ kg K ha}^{-1}$). Treatments T_4 and T_6 did not show significant differences from each other. In the current study, the amount of available K declined in the second year compared to the first year of wheat cultivation. But we observed that the enhancement of available K was significantly higher during the second year of cultivation than in the first year of cultivation. In this study, available K was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T_4 (9.02 and 25.56%), T_5 (17.23 and 33.06%), and T_7 (8.44 and 22.87%) as compared to treatment T_1 during the first and second years of cultivation, respectively (Figure 3C).

Influence of Integrated Potassium Fertilization on Yield of Wheat Grain Yield

The grain yield of wheat was recorded the maximum in treatment T_7 (5.39 ± 0.27 and $5.49 \pm 0.27 \text{ t ha}^{-1}$), followed by T_5 (5.05 ± 0.25 and $5.16 \pm 0.26 \text{ t ha}^{-1}$), T_4 (5.15 ± 0.26 and $5.25 \pm 0.26 \text{ t ha}^{-1}$), and T_2 (4.94 ± 0.25 and $5.05 \pm 0.25 \text{ t ha}^{-1}$) during the first and second years of wheat cultivation, respectively. But in the first and second years of wheat cultivation, treatments T_5 , T_4 , and T_2 did not show significant differences with each other. The least grain yield of wheat was recorded in treatment T_1 (5.39 ± 0.27 and $5.39 \pm 0.27 \text{ t ha}^{-1}$) during both years of cultivation. Among the

treatments, the grain yield of wheat was higher in the second year of cultivation than in the first year of cultivation. In this study, the grain yield of wheat was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T_4 (35.48 and 35.05%), T_5 (32.94 and 32.76%), and T_7 (41.71 and 41.14%) as compared to treatment T_1 during the first and second years of cultivation, respectively (Figure 4A).

Straw Yield

The straw yield of wheat was recorded the maximum in treatment T_7 (8.20 ± 0.41 and $8.98 \pm 0.45 \text{ t ha}^{-1}$), followed by T_5 (8.14 ± 0.41 and $8.77 \pm 0.44 \text{ t ha}^{-1}$), T_4 (8.18 ± 0.41 and $8.66 \pm 0.43 \text{ t ha}^{-1}$), and T_2 (8.13 ± 0.41 and $8.53 \pm 0.43 \text{ t ha}^{-1}$) during the first and second years of wheat cultivation, respectively. But in the first and second years of wheat cultivation, there was no significant difference with each other among the treatments. Low straw yield of wheat was recorded in treatment T_1 (7.30 ± 0.37 and $7.59 \pm 0.38 \text{ t ha}^{-1}$) during both years of cultivation. Among the treatments, the straw yield of wheat was higher in the second year of cultivation than in the first year of cultivation. In this study, the straw yield of wheat was significantly increased through integrated fertilization of K in the combination of MOP and FYM among treatments T_4 (12.09 and 14.05%), T_5 (11.57 and 15.51%), and T_7 (12.39 and 18.24%) as compared to treatment T_1 during the first and second years of cultivation, respectively (Figure 4B).

Biological Yield

The biological yield of wheat was recorded the maximum in treatment T_7 ($13.59 \pm 0.68 \text{ t ha}^{-1}$), followed by T_5 ($13.19 \pm 0.66 \text{ t ha}^{-1}$), T_4 ($13.33 \pm 0.67 \text{ t ha}^{-1}$), and T_2 ($13.07 \pm 0.65 \text{ t ha}^{-1}$) during the first year of cultivation. But, treatments T_5 , T_4 , T_2 , and T_6 did not show significant differences with each other. Besides, the biological yield of wheat during the second year of cultivation was recorded the maximum in treatment T_7 ($14.47 \pm 0.72 \text{ t ha}^{-1}$), followed by T_5 ($13.93 \pm 0.70 \text{ t ha}^{-1}$), T_4 ($13.91 \pm 0.70 \text{ t ha}^{-1}$), and T_2 ($13.58 \pm 0.68 \text{ t ha}^{-1}$). Although treatments T_7 , T_5 , and T_4 did not show significant differences

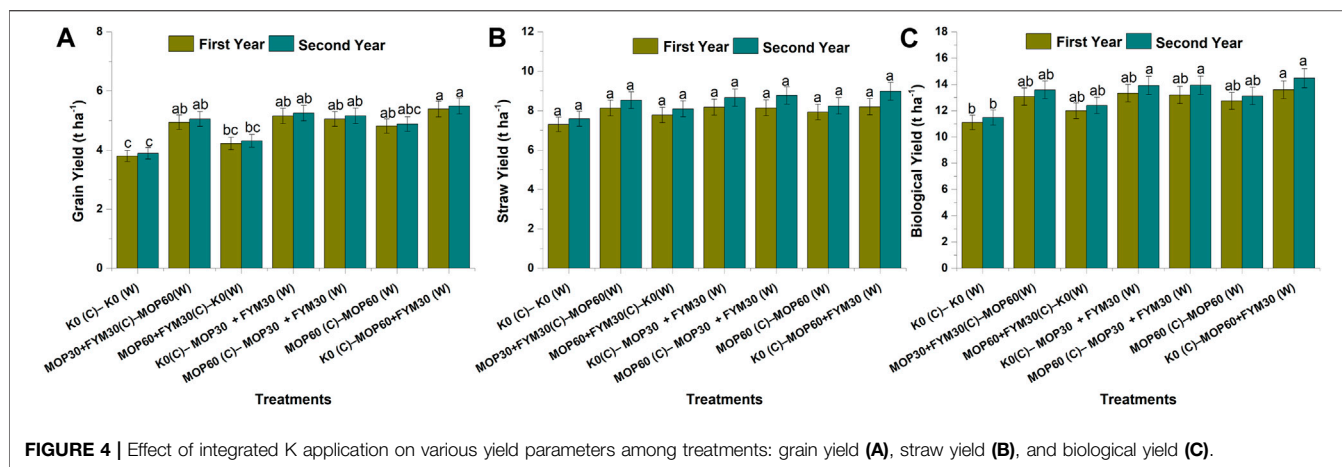


FIGURE 4 | Effect of integrated K application on various yield parameters among treatments: grain yield (A), straw yield (B), and biological yield (C).

with each other. The least biological yield of wheat was recorded in treatment T₁ during both years of cultivation. Among the treatments, the biological yield of wheat was higher in the second year of cultivation than in the first year of cultivation. In this study, the biological yield of wheat was significantly increased through integrated fertilization of K in the combination of MOP and FYM among the treatments T₄ (13.33 and 21.16%), T₅ (13.19 and 21.35%), and T₇ (13.59 and 26.00%) as compared to treatment T₁ during the first and second years of cultivation, respectively (Figure 4C).

Response of Integrated K Fertilization on Soil Health and Yield of Wheat First Year of Cultivation

The response of integrated K fertilization among the treatments and various parameters were analyzed through the principal component analysis and scatter plot matrix. The statistical analysis showed that data for the first year of cultivation possess two significant principal components, PC1 and PC2. Among them, PC1 showed a 97.80% level of variance and was more effective than PC2 that showed a 2.05% level of variance (Figure 5A). In the biplot graph, treatments were grouped into two clusters. The grouping among treatments strictly showed that the treatments (T₇, T₄, and T₅) employed with FYM (cluster I) and treatments (T₁, T₂, T₃, and T₆) employed without FYM (cluster II) were found as separate clusters in the first year of wheat cultivation. The details of both clusters are: cluster I [K₀(C)-MOP₃₀+FYM₃₀(W), MOP₆₀(C)-MOP₃₀+FYM₃₀(W), and K₀(C)-MOP₆₀+FYM₃₀(W)] and cluster II [K₀(C)-K₀(W), MOP₃₀+FYM₃₀(C)-MOP₆₀(W), MOP₆₀+FYM₃₀(C)-K₀(W), and MOP₆₀(C)-MOP₆₀(W)]. Although, cluster I was positively correlated with PC1 and negatively correlated with PC2, cluster II was positively correlated with both the principal components PC1 and PC2. However, various parameters were grouped into four clusters. The details of the obtained clusters are: cluster I (available N and available K); cluster II (alkaline phosphatase, dehydrogenase, bacterial population, and cellulose-degrading bacteria); cluster III (actinomycetes); and cluster IV (acid phosphatase,

K-solubilizing bacteria, phosphate-solubilizing bacteria, beta-glucosidase, FDA, available phosphorus, grain yield, straw yield, and biological yield). Cluster I and cluster II were positively correlated with PC1, while cluster I showed a positive correlation with PC2 and cluster II was negatively correlated with PC2. Cluster III showed a negative correlation with both PC1 and PC2. Cluster IV showed a negative correlation with PC1 and a positive correlation with PC2. Moreover, integrated fertilization of K through FYM along with MOP contributed to significantly improve the available K, available N, alkaline phosphatase, bacterial population, dehydrogenase activity, and population of cellulose-degrading bacteria (Figure 5A). The scatter plot matrix for the first year of cultivation showed that the treatments applied with FYM along with MOP (T₇, T₄, and T₅) and the various parameters (microbial population count, soil enzymatic activities, available nutrients in soil, and yield of wheat) showed strict regression coefficient (r^2) > 0.98. Based on the response on various parameters, the regression coefficient between the treatments applied with MOP and FYM were 0.99 (T₇ and T₄), 0.98 (T₇ and T₅), and 0.99 (T₄ and T₅), while the regression coefficient (r^2) among the treatments applied without MOP and FYM varied from 0.83 to 0.98. Moreover, the regression coefficients (r^2) among the treatments applied with MOP only were less than treatments used with MOP and FYM (Figure 5B). The integrated K-fertilization through MOP and FYM showed significant improvement among various parameters (microbial population count, soil enzymatic activities, available nutrients in soil, and wheat yield). The scatter plot matrix analysis revealed that integrated K fertilization applied with MOP and FYM was more promising to improve soil health and agricultural productivity than fertilization through MOP only or without MOP and FYM.

Second Year of Cultivation

The effect of integrated K fertilization among the treatments and various parameters was further analyzed for the second year of cultivation through the principal component analysis and scatter plot matrix. The statistical analysis showed that there were two significant principal components, PC1 and PC2. PC1 showed a

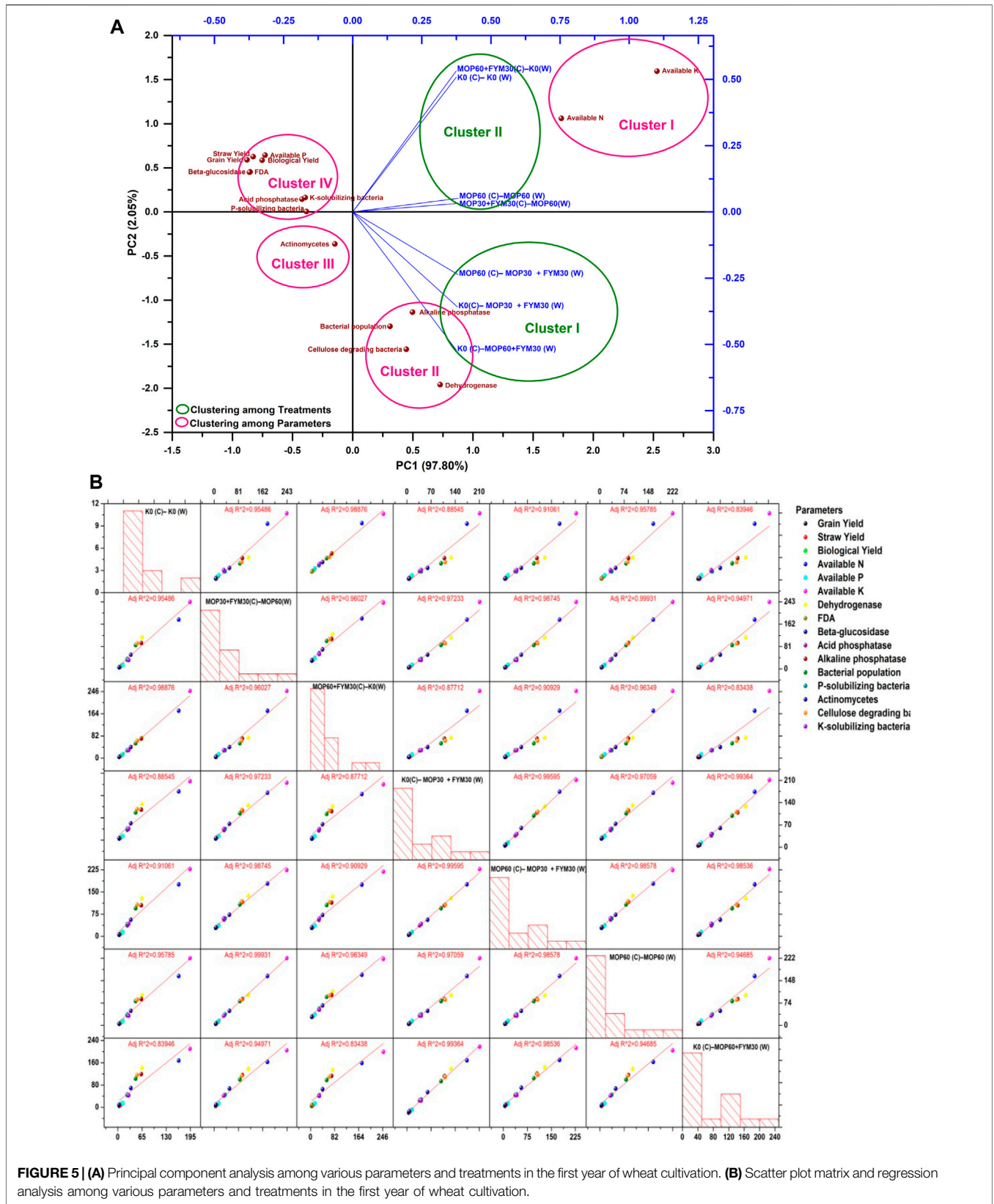


FIGURE 5 | (A) Principal component analysis among various parameters and treatments in the first year of wheat cultivation. **(B)** Scatter plot matrix and regression analysis among various parameters and treatments in the first year of wheat cultivation.

97.20% level of variance and was more significant than PC2 that showed a 2.46% level of variance (**Figure 6A**). In the biplot graph, treatments were grouped into two clusters. The grouping among treatments strictly showed that the treatments employed with FYM except for treatment T₆ (cluster I) and treatments employed without FYM (cluster II) were found as separate clusters. The details of the clusters are: cluster I [MOP₆₀ (C)–MOP₆₀ (W), K₀(C)–MOP₃₀ + FYM₃₀ (W), MOP₆₀ (C)–MOP₃₀ + FYM₃₀ (W), and K₀ (C)–MOP₆₀ + FYM₃₀ (W)] and cluster II [K₀ (C)–K₀ (W), MOP₃₀ + FYM₃₀(C)–MOP₆₀(W), and MOP₆₀ + FYM₃₀(C)–K₀(W)]. Cluster I was positively correlated with PC1 and negatively correlated with PC2. Besides, cluster II was positively correlated with both principal components PC1 and PC2. However, various parameters were grouped into four clusters. The details of the obtained clusters are: cluster I (available K and available N), cluster II (alkaline phosphatase, dehydrogenase, bacterial population, and cellulose-degrading bacteria), cluster III (actinomycetes and acid phosphatase), and cluster IV (K-solubilizing bacteria, phosphate-solubilizing bacteria, β-glucosidase, FDA, available phosphorus, grain yield, straw yield, and biological yield). Both cluster I and cluster II were positively correlated with PC1, while cluster I showed a positive correlation with both PC2 and cluster II showed a negative correlation with PC2. Cluster III showed a negative correlation with both PC1 and PC2. Cluster IV showed a negative correlation with PC1 and a positive correlation with PC2. Moreover, integrated fertilization of K through FYM along with MOP in the second year of wheat cultivation also significantly improved the available K, available N, alkaline phosphatase, bacterial population, dehydrogenase activity, and population of cellulose-degrading bacteria (**Figure 6A**). The scatter plot matrix for the second year of cultivation showed that the treatments applied with FYM along with MOP (T₇, T₄, and T₅) and the various parameters (microbial population count, soil enzymatic activities, available nutrients in soil, and yield parameters of wheat) also exhibited strict regression coefficient (r^2) > 0.98 similar to the first year of cultivation (**Figure 6B**). Based on the response on various parameters, the regression coefficient (r^2) for the second year of cultivation between the treatments applied with MOP and FYM were 0.98 (T₇ and T₄), 0.98 (T₇ and T₅), and 0.99 (T₄ and T₅), while the regression coefficient (r^2) among the treatments applied without MOP and FYM varied from 0.77 to 0.98. Moreover, the regression coefficient (r^2) between the treatments applied with MOP only was less than that between treatments used with MOP and FYM (**Figure 6B**). The integrated K fertilization through MOP and FYM showed significant improvement among various parameters (microbial population count, soil enzymatic activities, available nutrients in soil, and yield parameters of wheat). The scatter plot matrix analysis revealed that integrated K fertilization applied with MOP and FYM was also prominent in the second year of wheat cultivation and contributed to reclaim biological activities and productivity of soil compared to fertilization through MOP only or without MOP and FYM.

Moreover, the integrated fertilization of K through MOP and FYM showed that the cultivation of wheat crop in the consecutive two years recorded an enhancement in soil enzymatic activities

(11.59–57.22%), microbial populations (5.14–15.70%), available nutrients in the soil (7.60–16.54%), and crop yield (1.06–5.85%) during the second year of cultivation as compared to the first year of cultivation. In the second year of cultivation, the bacterial population count (6.57% by T₇), actinomycetes population (15.70% by T₅), and cellulose-degrading bacteria (5.14% by T₅ and 0.56% by T₇) were enhanced. The enzymatic activities were also enhanced, such as dehydrogenase (14.19% by T₄, 12.65% by T₅, and 13.48% by T₇), FDA (32.50% by T₄ and 37.70% by T₅), β-glucosidase (43.40% by T₄ and 57.22% by T₅), acid phosphatase (37.89% by T₄, 30.35% by T₅, and 32.10% by T₇), and alkaline phosphatase (11.59% by T₄ and 25.60% by T₅). Moreover, improved accessibility of nutrients in the soil (11.19% by T₄, 11.97% by T₅, and 12.37% by T₇ for available N; 12.96% by T₄, 13.07% by T₅, and 7.60% by T₇ for available P; 16.54% by T₄, 15.82% by T₅, and 14.53% by T₇ for available K) was recorded (**Figure 7**).

DISCUSSION

Microorganisms possess a high surface: volume ratio, because of which they exhibit intimate relationships with their native environments. A variation in microbial functioning in the soil is conceived as an index of soil reclamation and transient alterations to different perturbations (Pankhurst et al., 1995; Ezeokoli et al., 2020). In the present study, a significant enhancement of microbial communities like bacterial population, P-solubilizing bacteria, actinomycetes, K-solubilizing bacteria, and cellulose-degrading bacteria during the first and second years of wheat cultivation were found among treatments (T₄, T₅, and T₇) employed with integrated K fertilization through FYM and MOP in comparison to treatments employed with K *via* MOP only and without K treatment (**Figure 1**). Among these, treatment T₇ employed with 90 kg K ha⁻¹ recorded the highest microbial population count for bacterial population (1.03×10^8 and 1.15×10^8 cfu g soil⁻¹), P-solubilizing bacteria (0.46×10^4 and 0.44×10^4 cfu g soil⁻¹), actinomycetes (0.69×10^4 and 0.72×10^4 cfu g soil⁻¹), cellulose-degrading bacteria (1.16×10^4 and 1.23×10^4 cfu g soil⁻¹), and K-solubilizing bacteria (0.43×10^4 cfu g soil⁻¹ each) during both years of cultivation. In comparison to chemical fertilizers, integrated fertilization of K showed the most prominent response on microbial activities and biomass. Firstly, the integrated fertilization of K furnished abounding organic matter for the growth and development of living soil microbial communities. Secondly, integrated fertilization of K showed a beneficial response for improving the growth of plant roots, which also imparted soil organic matter for microorganisms (Gong et al., 2009; Enebe and Babalola, 2020; Wu et al., 2020; Zhu et al., 2020).

Various enzymes in the soil contribute a significant role. Dehydrogenase activity is regarded the most prominent index of microbial activities, which occurs in viable cells only and indicates the sum of oxidative activities mediated by soil microfauna (Nannipieri et al., 1990). The dehydrogenase activity was increased due to integrated K management treatments, as dehydrogenase activity is

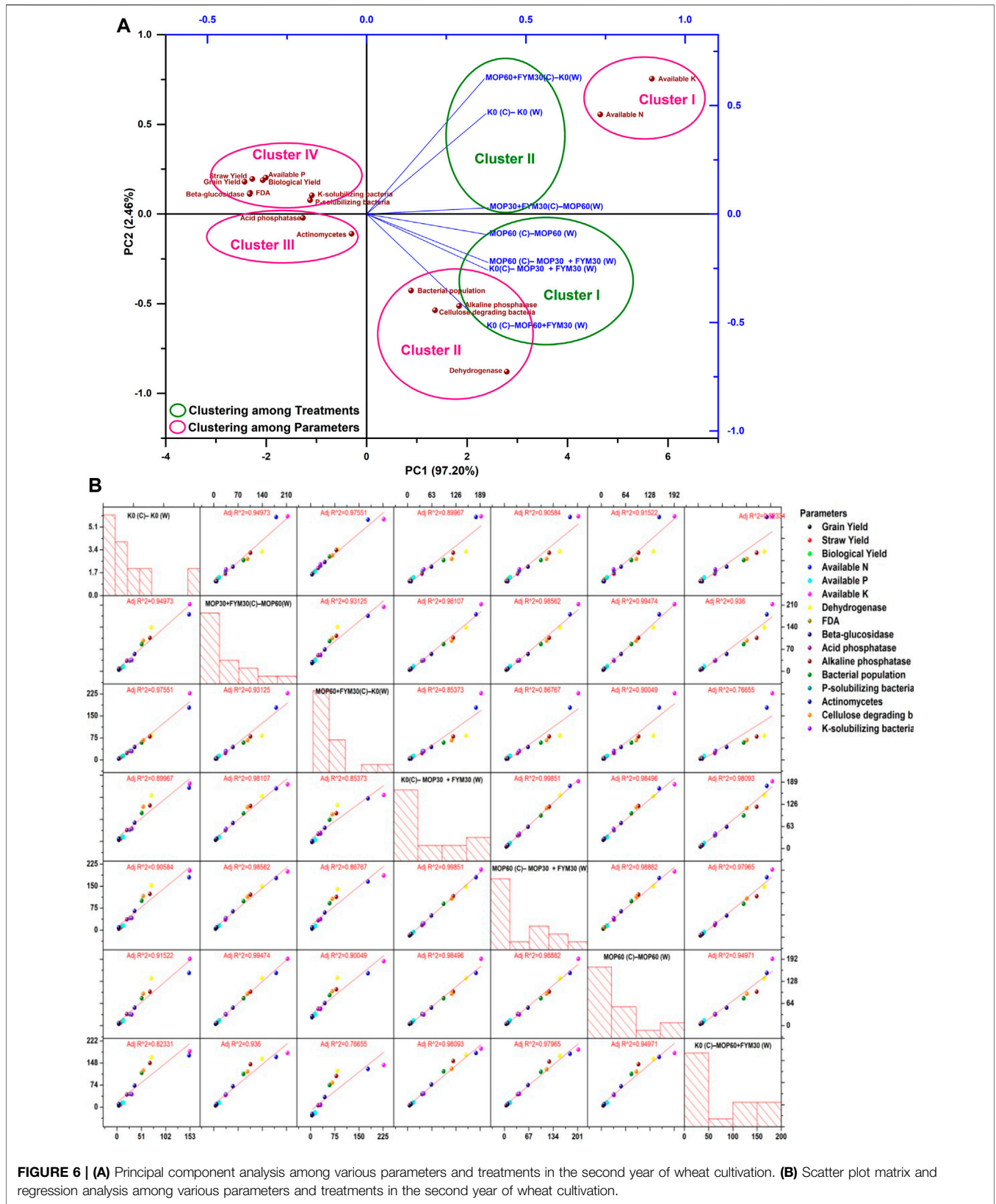
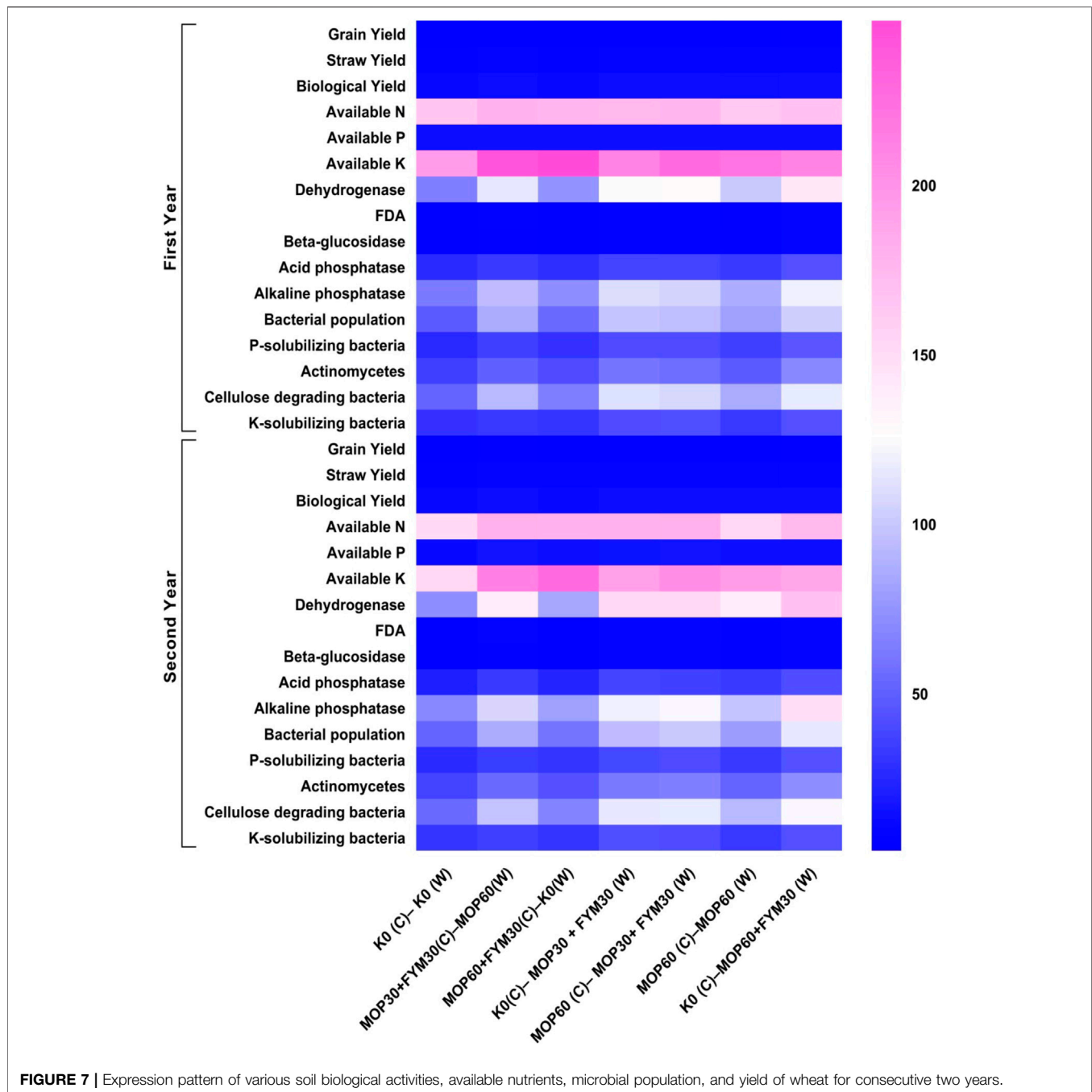


FIGURE 6 | (A) Principal component analysis among various parameters and treatments in the second year of wheat cultivation. **(B)** Scatter plot matrix and regression analysis among various parameters and treatments in the second year of wheat cultivation.



influenced by the amount of organic matter included in the soils (Pancholy and Rice, 1973; Meena and Rao, 2021). Thus, integrated K fertilization practices that have FYM with the easily decomposable component for supplying K possess a more substantial influence on soil microorganisms' metabolic activity leading to an enhancement in the dehydrogenase activity in the soil. In this study, dehydrogenase activity was recorded the highest in treatment T_7 (142.0 ± 7.1 and $167.0 \pm 8.35 \mu\text{g TPF g soil}^{-1} \text{d}^{-1}$) followed by T_5 (128.0 ± 6.4 and $152.0 \pm 7.6 \mu\text{g TPF g soil}^{-1} \text{d}^{-1}$), and T_4 (129.0 ± 6.45 and $152.0 \pm 7.6 \mu\text{g TPF g soil}^{-1} \text{d}^{-1}$), while poor dehydrogenase activity was observed in treatment (T_1) that did not use K fertilization, which

is consistent with the earlier studies (Liu et al., 2010; Heidari et al., 2016).

Those enzymes which act to hydrolyze anhydrides and esters of phosphoric acid are broadly classified as phosphatases. Phosphatases are crucial as they are involved in the conversion of organic P to available P (Lee Taylor and Sinsabaugh, 2015) for plant uptake. In this study, the treatments applied with integrated fertilization of K had significantly affected alkaline and acid phosphatase activities. The alkaline and acid phosphatase activities were found lower in control (T_1) and showed significantly increased activities

arranged from 43.75 to 114.49% among the treatments applied with integrated fertilization of K through FYM and MOP or MOP alone during both the years. Earlier reports showed that acid and alkaline phosphatase activities had been enhanced through both inorganic and integrated fertilization (Mandal et al., 2007; Garg and Bahl, 2008; Heidari et al., 2016). K application led to better crop productivity and higher root biomass development in preceding corn crop (Kumar et al., 2018) which was the reason for increased activity of alkaline and acid phosphatase enzymes in the soil, whereas under integrated K management treatments, application of FYM was responsible for enhanced diverse phosphate-solubilizing bacterial activity.

β -glucosidase is one of the enzymes that contributed to the degradation of biomass and is considered as an early indicator of variations in soil characteristics (Ekenler and Tabatabai, 2003). The fluorescein diacetate [3',6'-diacetyl fluorescein (FDA)] assay is generally utilized to examine hydrolytic enzymatic activities of soil microbial communities (e.g., fungi and bacteria) (Alkorta et al., 2003; Liu et al., 2007). In the present study, the integrated fertilization of K showed enhanced β -glucosidase activity (9.8 ± 0.49 and 10.2 ± 0.51 $\mu\text{g PNP g soil}^{-1} \text{h}^{-1}$) and FDA (9.5 ± 0.48 and 9.6 ± 0.48 $\mu\text{g fluorescein g soil}^{-1} \text{h}^{-1}$) by treatment T₇ activity in comparison to treatments (T₂, T₃, and T₆) employed with K by MOP only or by treatment T₁ used without K during both years of cultivation (Figure 2). The increase in β -glucosidase and FDA activities through integrated fertilization of K was found because of high accessibility of easily decomposable organic components or organic carbon through introduced FYM for the metabolism, development, and growth of soil microorganisms (Gopinath et al., 2008; Gong et al., 2009; Burns et al., 2013; Heidari et al., 2016). Higher β -glucosidase and FDA activities recorded in treatments employed with K by MOP alone confirmed previous findings (Rani et al., 2014; Singh et al., 2015; Heidari et al., 2016).

Accessibility of N, P, and K nutrients reduced after wheat harvest (Figure 3). The regular mining of various nutrients through crops reduces available nutrients irrespective of applied nutrients (Johri and Yadav, 2006; Ramamurthy et al., 2009). In the present study, the treatment used with integrated K-fertilization recorded enhancement in the availability of different nutrients that ranged from 2.43 to 22.87%, which is the property of FYM to supply organically bound nutrients such as N and P in a slow manner (Diacono and Montemurro, 2011; Choudhary and Sureshky, 2013). The addition of FYM in integrated K management treatments increases the process of weathering in nutrient-bearing minerals, which aids the dissolution of insoluble minerals and makes plant nutrients available. Furthermore, FYM slowly adds available C in the soil, which acts as an energy source to favor highly diverse microbial communities with different functional properties, which supports dissolution and nutrients availability to crop plants (Wolf and Wagner, 2005; Heidari et al., 2016).

In the present study, the treatments employed with integrated fertilization of K exhibited substantial enhancement in wheat yield up to 12.39–41.71% and 18.24–41.14% in the first and second years of cultivation, respectively (Figure 4). The maximum yield was found in treatment T₇ employed with

90 kg K ha⁻¹ (30 kg K by FYM and 60 kg K by MOP) in wheat. The utilization of 90 kg K ha⁻¹ enhanced the availability of K in the soil. The available K is essential to several plant metabolic pathways that include photosynthesis in plants, photosynthates translocation to different plant parts, synthesis of protein, and plant enzymes activation (IPNI, 1998). Among treatments, integrated K fertilization through FYM supplies nitrogen, phosphorus, and potassium along with micronutrients in readily available forms to the crop plants by the process of bio-decomposition, which helps in achieving higher yields. A study on integrated K fertilization through FYM and MOP showed an important enhancement in yield compared to 100% NPK and 100% NP fertilizers because of the high abundance of macro- and micronutrients (Kumar et al., 2015). Various levels of FYM and NPK, either single or in combinations, exhibited a vital influence on wheat yield (Rehman et al., 2008). Moreover, the enhanced K fertilization showed a prominent rise in wheat yield and growth (Mehdi et al., 2001).

The strict positive relationship exhibited that enzymatic activities and microbial population count contributed an important role in improving the yield (Figure 5A and Figure 6A). Moreover, the integrated fertilization of K in the combination of FYM and MOP showed more effectiveness among the treatments in comparison to MOP or FYM only. The treatments also showed distinct relationships with each other based on the regression analysis of various parameters (Figure 5B and Figure 6B). By the release of nutrients, the activity of microbes and enzymes assists in biomass transformations. The enhancement in microbial activities indirectly exhibited an enhancement in microbial biomass that acted as a low but reliable source for these nutrients.

CONCLUSION

This study revealed that integrated fertilization of FYM showed a significant role to improve soil health and yield of crops. Integrated fertilization through FYM modulates microbial population and soil enzymatic activities that enhance the availability of nutrients (N, P, and K) and yield parameters. The high availability of nutrients in the soil helps plants for their growth and development. Thus, the consecutive use of integrated fertilization of K through FYM and MOP exhibited the most promising impact on soil biological activities and yield of wheat, followed by the reduction in the use of chemical fertilizers. Less chemical fertilizers introduced in agricultural lands may benefit farmers economically and enhance soil health or soil fertility. Thus, the use of FYM as an alternate to K fertilization could be helpful to reclaim soil fertility and farmers' economy.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SK contributed to investigation, conceptualization, formal analysis, methodology, validation, and writing—original draft; SD contributed to supervision, validation, and writing—review and editing; SB contributed to data curation and writing—review and editing; MR contributed to visualization, validation, and writing—review and editing; SAK contributed to formal analysis and validation; SuK supported in writing—review and editing; DK supported in visualization; and LM contributed to formal analysis and data curation.

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