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Synergistic Effects of Integrated Fertilisation and Amendments on Protein Content, Yield and Soil Fertility in Acid *Alfisols*

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Abstract

A field experiment was carried out on maize during *kharif* 2023 at CSK HPKV, Palampur, to study the effect of integrated fertilisation and amendments on maize nutritional quality, yield and soil fertility in acid soils. The experiment consisted of ten treatments, replicated thrice. Results revealed that the highest crude protein (98.5 g kg^{-1}), P content (3.9 g kg^{-1}), grain and stover yield (62.36 and 95.3 q ha^{-1}) was recorded under 100% NPK + 10 t FYM ha^{-1} + lime incorporation @ 100% LR, being statistically at par with 100% NPK + 10 t FYM ha^{-1} + lime incorporation @ 1/10th LR in furrow. Soil attributes, including pH, OC and CEC, increased by 14.8, 27.7 and 32.3% over control, respectively. The highest available N and K (365 and 269 kg ha^{-1}) were recorded under 10 t FYM ha^{-1}, while maximum available P (21.50 kg ha^{-1}) was under 100% NPK + 10 t FYM ha^{-1} + lime incorporation @ 100% LR.

Keywords: Acid soils, Lime, Maize yield, Soil attributes, FYM

Since ancient times, agriculture has served as the fundamental pillar of global food security and has contributed substantially to economic development. Maize (*Zea mays* L.) is the third leading crop grown worldwide, after rice and wheat[1]. As a queen of cereals, it is one of the most versatile crops, having high genetic potential, supporting food, feed and industrial sectors. In India, maize is grown over an area of 12.02 million hectares (Mha) with a total production of 42.2 million tonnes (Mt) (5th largest producer) and productivity of 3.51 tonnes ha^{-1} (t ha^{-1})[2]. During 2023-24, the annual production of maize in Himachal Pradesh was estimated to be about 0.75 Mt and[2] is grown over an area of 0.25 M ha of land with an average productivity of 3 t ha^{-1}, respectively. Despite India's notable share in global maize production, the national and state-level yields still lag behind the global average, i.e., 6.2 t ha^{-1} [1]. The production is constrained owing to declining soil fertility, soil acidity in the region, erosion and intensive farming.

The soil acidity not only limits nutrient availability but also reduces fertiliser use efficiency and crop performance. In India, 28% of the country's land suffers from varying degrees of soil acidity (4.5-6.5), and in

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Himachal Pradesh, the extent of acidic soil is 1.74 m ha[3]. Maize, being sensitive to aluminium toxicity and low phosphorus availability, often exhibits restricted root growth and reduced biomass accumulation under acidic conditions[4]. The productivity losses in pH range 5.5– 6.5, 4.5–5.5 and less than 4.5 are up to 10%, 10–25% and more than 50%, respectively[5]. Moreover, the widespread reliance on fertilisers alone, primarily nitrogen, phosphorus and potassium (NPK), has improved crop yields in the short term but has often led to declining/stagnant yield, organic carbon depletion, low nutrient use efficiency and reduced soil fertility in the long run[6].

In this context, integrated nutrient management has emerged as a key strategy for addressing soil degradation in acidic environments. Among the available interventions, the combined use of inorganic fertilisers with organic manures like Farmyard Manure (FYM) and amendments (lime) has shown considerable potential[7]. Sankhyan *et al.*,[8] reported that NPK fertilisers with FYM or lime significantly boosted wheat yield, with FYM increasing yield by 39.9% and lime by 29.4% over sole 100% NPK, respectively. FYM contributes to soil fertility through the addition of organic carbon, slow-release nutrients and enhanced microbial activity, while also improving soil structure, porosity, moisture retention and cation exchange capacity[9]. Lime application directly neutralises exchangeable acidity, supplies Ca and Mg and improves CEC, phosphorus availability by reducing fixation by Fe and Al oxides[10,11]. Together, these inputs have the potential to improve overall soil health, thereby increasing nutrient uptake and enhancing crop performance. Despite the well-recognised benefits of FYM and lime, their synergistic effects on maize grain quality, yield and soil fertility remain insufficiently quantified. Considering the importance and scarcity of information available, the present study was designed with the objective to evaluate the synergistic effects of integrated fertilisation and amendments on maize grain nutritional quality, yield and soil fertility.

MATERIALS AND METHODS

An experiment was conducted during *kharif* 2023 in the ongoing experiment, which has been in progress since *kharif* 2019, at the Research Farm of the Department of Soil Science, Chaudhary Sarwan Kumar Krishi Vishvavidyalaya, Palampur, Himachal Pradesh (India). The experimental farm is located at 32˚7' N latitude and 76˚31' E longitude at an altitude of about 1290 meters above mean sea level (amsl). The study site falls under the Mid Hills Sub-Humid Zone. The climate of the study area is characterised by mild summers and severe winters. The total rainfall received during the crop growth period was 2219 mm, whereas the average minimum and maximum temperatures were 13.7 and 27.8 °C, respectively. The soil of the study area was silt loam in texture (*Typic Hapludalf*) with an acidic pH (5.49), CEC (11.9 c mol (p^+) kg^{-1}), medium in organic carbon (8.34 g kg^{-1}), available N (291 kg ha^{-1}), P (11.2 kg ha^{-1}) and K (228 kg ha^{-1}).

The field trial was laid out in a complete randomised block design (RBD), comprised of 10 treatments, *viz.* T_1, Control; T_2, 100% NPK; T_3, 100% NPK + 5 t FYM ha^{-1}; T_4, 100% NPK + 10 t FYM ha^{-1}; T_5, 100% NPK + lime (full dose through broadcasting); T_6, 100% NPK + lime ($1/10^{th}$ dose through furrow application); T_7, 100% NPK + 5 t FYM ha^{-1} + lime (full dose through broadcasting); T_8, 100% NPK + 10 t FYM ha^{-1} + lime (full dose through broadcasting); T_9, 100% NPK + 5 t FYM/ha + lime ($1/10^{th}$ dose through furrow application); T_{10}, 100% NPK + 10 t FYM ha^{-1} + lime ($1/10^{th}$ dose through furrow application), replicated thrice. Maize (variety-K 25 Gold) was sown in the third week of June in 12 m^2 plots with a spacing of 60 × 20 cm. The recommended dose of N, P and K for the crop was 120, 60 and 40 kg/ha, respectively. The nutrients were supplied through urea, single super phosphate (SSP) and muriate of potash (MOP) for all treatments except T_1 (control). Half dose of N and full dose of P and K were applied at the time of sowing of maize in treatments T_2-T_{10}. Half of the remaining nitrogen was top-dressed in two equal splits at knee high and pre-tasseling stage. Farmyard manure (FYM) was incorporated into the soil @ 5 t ha^{-1} for treatments T_3, T_7 and T_9 and @10 t ha^{-1} for treatments

T_4, T_8 and T_{10} on a dry weight basis and thoroughly mixed in the soil before sowing. The lime requirement was assessed using the Shoemaker Mclean, and Pratt buffer method[12], and a full dose of marketable lime (4 t ha^{-1} $CaCO_3$) was evenly spread across the soil surface and thoroughly mixed in the soil for treatments T_5, T_7 and T_8. Alternatively, T_6, T_9 and T_{10} received a $1/10^{th}$ dose of lime (0.4 t ha^{-1}), applied in furrows. Two levels of lime were used to evaluate the potential for reducing lime application while maintaining maize productivity. The standard package of practices was followed for raising the crop.

The grain and stover yields were recorded after the harvest of maize. The grain yield of maize was calculated at 15.5 per cent moisture content, whereas the stover yield of maize was recorded on air dry basis. The data so obtained was expressed on a hectare basis. Five randomly selected cobs were taken, and the maize grain samples were dried in an oven at 60˚C. After drying, they were ground in a Wiley mill fitted with stainless steel (< 1 mm). For further analysis, the samples were stored in paper bags. The concentration of total nitrogen in grain samples was assessed using the Micro Kjeldahl method[13] and P by the vanado molybdo-phosphoric acid method[13]. Crude protein content was calculated by multiplying a factor (6.25) by the nitrogen content given by Jones[14].

Soil samples were drawn at a depth of 0-0.15 m after the harvest of maize with a stainless steel screw-type auger and were air-dried. The samples were then ground using a wooden pestle and mortar to pass through a 2 mm sieve (0.5 mm for organic carbon) and were then stored in polyethene bags. The pH of the soil was determined in a pH meter using a (1:2.5) soil: water suspension[15]. Organic Carbon (OC) was calculated using the rapid titration[16], Cation exchange capacity was determined using Neutral normal ammonium acetate[17]. Further available N was determined using the alkaline permanganate method[18], available P was determined using the colourimetric method[19] and available K was determined using the flame photometric method[13].

Statistical Analysis

Statistical analysis was performed on the data obtained from examination of the plant and soil characteristics. The data were interpreted using the ANOVA of randomized block design. Using RStudio 4.4.2. The Fisher's Least Significant Difference test was performed to determine the grouping of means at 95% probability.

RESULTS AND DISCUSSION

The results illustrated significant variation in maize grain quality traits among different integrated fertilisation and amendment strategies. Crude protein content in grains increased from 81.4 g kg^{-1} (T_1) to 98.5 g kg^{-1} (T_8). The highest crude protein was recorded under treatment T_8, resulting in an increase of 21% over control (T_1) and was at par with T_7, T_9 and T_{10}. Mean phosphorus (P) concentration ranged from 2.3 g kg^{-1} (T_1) to 3.9 g kg^{-1} (T_8 and T_{10}) [Figure 1], demonstrating 69.56% increase over the control. Also, improvement in crude protein and P content was observed in T_3 to T_6 in comparison to T_1 and T_2.

The significantly higher crude protein and P content were recorded under combined NPK, FYM and lime treatments (T_8, T_{10} and T_7). This might be partly attributed to the application of lime on 100% LR basis or $1/10^{th}$ LR in furrow, which reduces nutrient toxicity (Al^{3+}, Mn^{2+}) and surges soil pH, thereby enhancing microbial nitrogen mineralisation and reducing P fixation in Fe and Al oxides[4]. Concurrently, FYM improves CEC, supplies organic nitrogen and phosphorus, stimulates microbial biomass, resulting in a sustained release of mineral N and P during the growth period[11]. Further, FYM contributes to improved root growth that likely facilitated greater N and P acquisition, explaining the progressive increase in T_4 (10 t FYM ha^{-1}) and T_3 (5 t FYM ha^{-1})[6]. Lime-based treatments (T_5:100% LR incorporation and T_6 :$1/10^{th}$ LR in furrow) also showed moderate enhancement in grain quality traits, indicating partial correction of soil constraints without FYM.

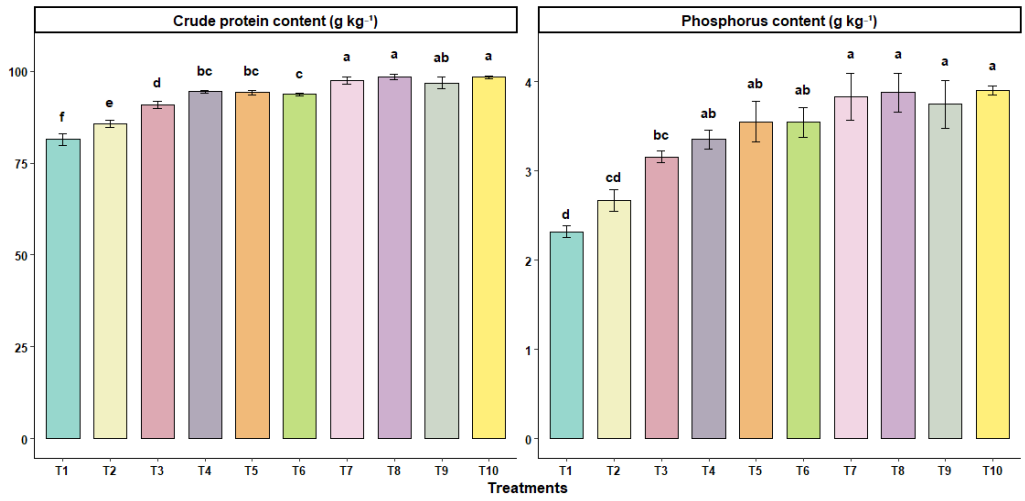


Figure 1. Effect of integrated fertilisation and soil amendments on crude protein content (g kg^{-1}) and phosphorus content in maize grains.

(Bars represent mean values for different treatments, error bars indicate the standard error of the mean (± SE), and the letters above the bars denote statistical grouping based on a post-hoc multiple comparison test (DMRT) performed at the 5% level of significance ($p \leq 0.05$)).

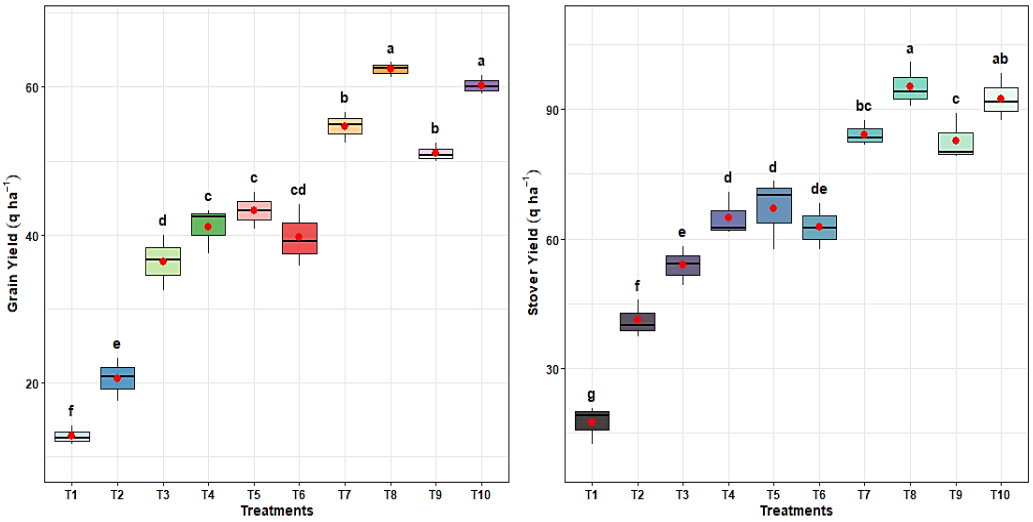


Figure 2. Effect of integrated fertilisation and soil amendments on the grain (left) and stover yield (right) (q ha^{-1}) of maize.

(The red dots represent the mean value for each treatment group, and the horizontal black line inside the box represents the median, while the letters above the box plots denote statistical grouping based on a post-hoc multiple comparison test (DMRT) performed at the 5% level of significance ($p \leq 0.05$)).

Grain and stover yield of maize (Figure 2) reflected a strong response towards fertilization and amendment strategies used. Grain yield ranged from 12.78 q ha^{-1} (T_1) to 62.36 q ha^{-1} (T_8). Highet grain yield was recorded under T_8, having 387.9% increase over the control and was statistically at par with T_{10}

(60.28 q ha^{-1}). Similarly, stover yield varied from 17.5 to 95.3 q ha^{-1} across treatments. Maximum stover yield was attained under T_8 (95.3 q ha^{-1}), which was at par with T_{10} (92.5 q ha^{-1}). 100% NPK + 10 t FYM ha^{-1} + @ 100% lime incorporation registered a 444.6 and 131.8% increase in stover yield over T_1 and T_2 (41.1 q ha^{-1}).

Treatments T_8 and T_{10} produced the highest grain and stover yield, followed by $T_{7,}$ which reflected a strong synergism between NPK fertilisers, FYM and lime, where each constituent compensates for the limitations. Lime neutralises soil acidity and eliminates root growth constraints, further FYM enhances nutrient retention, microbial-mediated nutrient cycling, and NPK ensures adequate nutrient supply throughout crop growth[20]. Plots receiving either FYM (T_3 and T_4) or lime (T_5 and T_6) alone resulted in only restrained yield, reflecting partial correction of soil constraints. In T_3 and $T_{4,}$ FYM supported vegetative growth and grain filling *via* supplying organic carbon, enhancing porosity, CEC and microbial activity[21], however, without lime, soil acidity persisted, limiting root expansion and restricting the uptake of Ca, Mg and P, thereby capping yield potential[6]. Likewise, in lime-treated plots (T_5 and T_6), the amount of FYM constrained the yield benefits. Thus, findings strongly emphasise that the integrated application of NPK fertilisers with FYM and lime is essential for achieving sustainable and higher maize productivity in acidic soils.

Soil Fertility Attributes

Soil pH, a key factor influencing nutrient availability in the soil, exhibited a clear distinction across treatments, rising from 5.44 (T_1) to 6.25 (T_8). Higher pH values were observed in treatments T_5 to T_{10} as compared to T_1 to T_4 (Table 1). T_8 (6.25) and T_7 (6.22) recorded the highest pH, followed by T_5 (6.19), indicating maximum amelioration of soil acidity. This might be

Table 1. Effect of integrated fertilisation and soil amendments on pH, OC (g kg^{-1}) and CEC (cmol (p^+) kg^{-1}) after maize harvest

Treatment	pH	SOC	CEC
T_1-Control	5.44	8.53	11.85
T_2-100% NPK	5.53	8.90	12.32
T_3-100%NPK+5t FYM ha^{-1}	5.68	9.67	13.95
T_4-100% NPK + 10 t FYM ha^{-1}	5.74	9.96	14.60
T_5-100% NPK+ lime incorporation @ 100% LR	6.19	9.28	14.35
T_6-100% NPK+ lime incorporation @ $1/10^{th}$ LR in furrow	5.83	9.10	13.30
T7- 100% NPK + 5 t FYM ha^{-1}+ lime incorporation @ 100% LR	6.22	10.67	15.17
T_8- 100% NPK + 10 t FYM ha^{-1}+ lime incorporation @ 100% LR	6.25	10.90	15.68
T_9-100% NPK + 5 t FYM ha^{-1}+ lime incorporation @ $1/10^{th}$ LR in furrow	5.88	10.53	14.87
T_{10}-100% NPK + 10 t FYM ha^{-1}+ lime incorporation @ $1/10^{th}$ LR in furrow	5.90	10.84	15.32
CD (p=0.05)	-	0.69	0.76
Initial	5.49	8.34	11.9

attributed to the 100% lime requirement application, which neutralises exchangeable acidity by replacing exchangeable H^+ and Al^{3+} ions with Ca^{2+} and Mg^{2+} [22,23]. The maximum pH under T_7 and T_8 resulted from the combined application of lime (@100% LR) and FYM (5 and 10 t ha^{-1}), where FYM enhanced lime efficiency by improving buffering capacity, supplying basic cations and reducing re-acidification[21]. The lowest pH under the control reflects the inherent acidity of the soil, supported by leaching of base cations under high rainfall conditions.

Further, application of 100% NPK + @ 10 t FYM ha^{-1} + 100% LR recorded the highest Organic Carbon (OC) content (10.90 g kg^{-1}), reflecting a 27.79 and 22.47% increase over T_1 and T_2, respectively. The highest OC under integrated treatments, i.e., T_7 to T_{10}, might be owing to direct application of FYM (@ 10 t ha^{-1}) and liming. 100% LR improved pH, facilitated microbial efficiency and stabilised organic matter by reducing acidity-induced decomposition losses, while FYM supplies fresh Organic Carbon (OC), resulting in greater OC accumulation[10,24]. Lime-only plots (T_5 and T_6) also showed moderate OC improvement owing to crop cycles over 6 years and residue return, but lacked direct carbon input[23]. Further, CEC ranged from 11.85 (T_1) to 15.68 c mol(p^+) kg^{-1} (T_8). T_8 recorded the highest CEC and was at par with T_7 and T_{10}. This is credited to the synergistic effect of FYM and lime, where organic matter increased exchange sites and higher pH enhanced charge development[25]. Additionally, a rise in CEC in T_3 and T_4 highlights the increasing soil organic matter, which contributes negatively charged functional groups and enhances cation retention[26]. The relatively high CEC under lime-based treatments (T_5 and T_6) suggested that liming increases pH-dependent charges on clay[27], thereby improving exchange capacity; however, the lower CEC under T_6 indicated that localised lime application was less effective than full incorporation.

Significant variations in nutrient availability were recorded owing to different fertilisation and amendment levels used. Available nitrogen ranged from 267 to 365 kg ha^{-1} (Figure 3). Treatment T_4 recorded the highest available N, having 36.70 and 22.4 8% increase over T_1 and T_2, respectively. Also, T_4 was statistically superior to T_5 and T_6, while it remained at par with T_{10} and T_8 (360 and 356 kg ha^{-1}). Treatments T_7 to T_{10} maintained relatively high available N *via* combined effects of FYM and lime; however, their values remained slightly lower than T_4, likely due to greater crop N uptake associated with higher biomass and grain yields[23]. The highest available N in T_4 is primarily due to the large FYM application (10 t ha^{-1}), which contributed substantial organic nitrogen and increased microbial mineralization[22]. However, FYM-derived nitrogen is released progressively and often asynchronously with

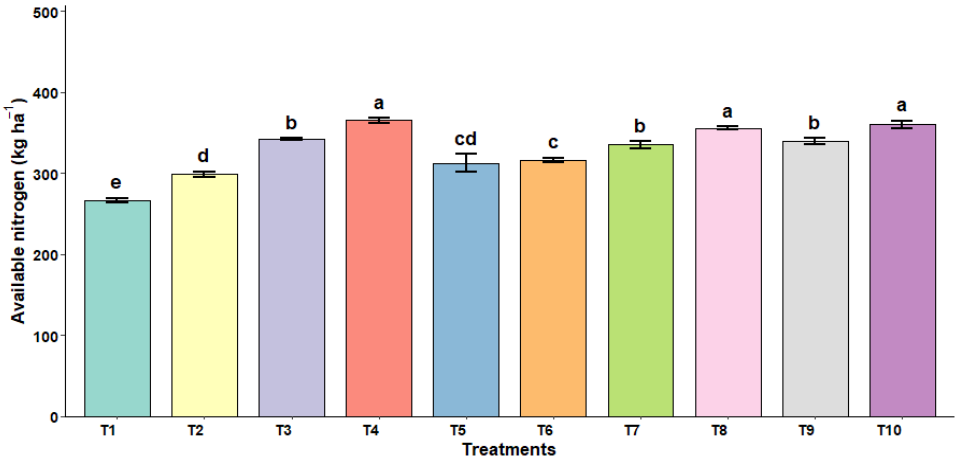


Figure 3. Effect of integrated fertilisation and soil amendments on available N (kg ha^{-1}) after maize harvest.

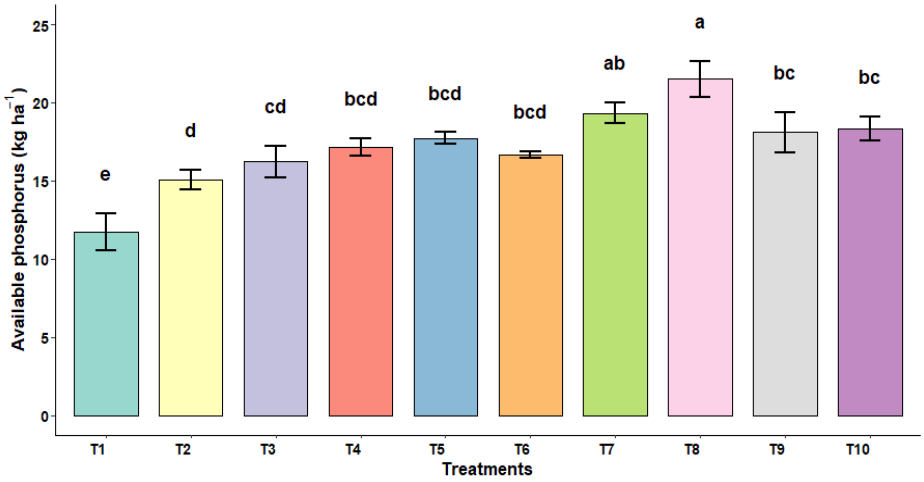


Figure 4. Effect of integrated fertilisation and soil amendments on available P (kg ha^{-1}) after maize harvest.

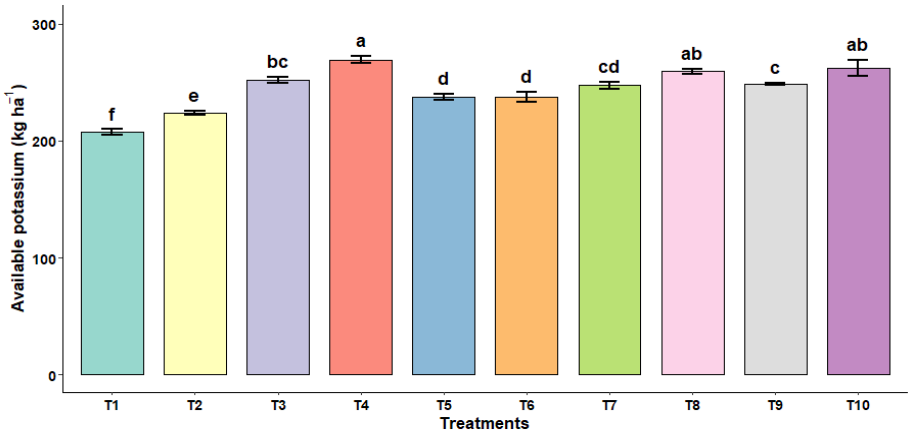


Figure 5. Effect of integrated fertilisation and soil amendments on available K (kg ha^{-1}) after maize harvest.

(Bars represent mean values for different treatments, error bars indicate the standard error of the mean (± SE), and the letters above the bars denote statistical grouping based on a post-hoc multiple comparison test (DMRT) performed at the 5% level of significance ($p \leq 0.05$)).

peak crop demand, resulting in higher residual soil N at sampling rather than during plant uptake[28].

Available P increased steadily from T_1 (11.73 kg ha^{-1}) to T_5 (17.72 kg ha^{-1}), showing a significant improvement over T_1, T_2 and T_3. Moreover, T_8 (21.50 kg ha^{-1}) recorded the highest available P, the increase being 83.30 and 42.57% over T_1 and T_2, respectively and was at par with T_7 (19.33 kg ha^{-1}) (Figure 4). This can be ascribed to effective soil acidity correction through 100% lime application combined with FYM, which elevated soil pH to near-neutral levels, minimised Fe–Al–P interactions and enhanced P solubility[9,29]. In contrast, treatments with localised lime application (T_6, T_9 and T_{10}) showed moderate P availability, indicating partial reduction of P fixation confined to the root zone rather than the bulk soil[11]. Gradual augmentation in

available P under FYM treatments (T_3 and T_4) can be attributed to the release of organic acids, which form complexes of Fe and Al, thereby reducing P fixation[30]. Despite this, soil acidity still limited maximum P build-up. Further, the highest available K (269 kg ha^{-1}) was recorded in plots receiving 10 t FYM ha^{-1} (T_4), showing a 29.89 and 20.24% increase over T_1 and T_2, respectively (Figure 5). T_4 was statistically at par with T_{10} and T_8 (262 and 259 kg ha^{-1}), but significantly superior to T_5 and T_6. Treatments T_3, T_7 and T_9 (252, 247 and 248 kg ha^{-1}) recorded intermediate K values. The marked increase in available K under FYM plots (T_3 and T_4) can be credited to the direct K contribution from FYM and improved cation retention[29,30]. Notably, treatments with higher grain and stover yields exhibited slightly lower residual K compared to FYM only plots, indicating greater K uptake and utilisation under improved growth conditions[11].

CONCLUSION

It can be concluded from the above study that integrated application of fertilisers, FYM and lime, mainly at higher FYM rates (10 t FYM ha^{-1}) with full (T_8) or 1/10th lime requirement in furrow (T_{10}), expressively enhanced maize grain nutritional quality, yield and soil fertility by improving soil-rhizospheric environment. Their combined use proved superior to individual applications or no inputs, offering a sustainable strategy for improving maize productivity and soil fertility in the acid soil regions of the Western Himalayas.

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CONFLICT OF INTEREST

The authors hereby declare that there is no conflict of interest among the authors.

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AUTHORS CONTRIBUTION

SM: conducted the experiment, data curation and wrote the original manuscript. RPS, NKS and RK: conceptualize the research programme, methodology, provided resources and edited the manuscript. P: Analyzed the data, figures and manuscript review.