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Zinc fortification and legume incorporation in forage based cropping systems: Implications for yield and nutrient dynamics

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Abstract

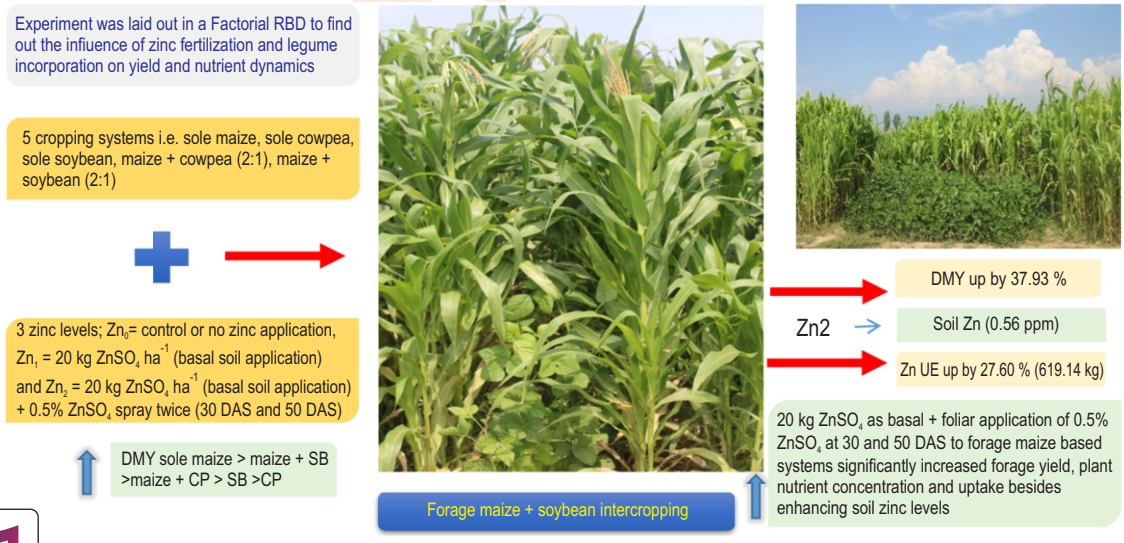
Aim: To evaluate the synergistic effects of legume intercropping and zinc fortification on forage yield, and plant and soil nutrient dynamics.

Methodology: The experiment was laid out in a Factorial Randomized Block Design. Treatment combinations included five cropping systems, *i.e.,* sole maize, sole cowpea, sole soybean, maize + cowpea (2:1), maize + soybean (2:1) and three zinc levels; Zn_0= control or no zinc application, Zn_1 = 20 kg $ZnSO_4$ ha^{-1} (basal soil application) and Zn_2 = 20 kg $ZnSO_4$ ha^{-1} (basal soil application) + 0.5% $ZnSO_4$ sprayed twice (30 DAS and 50 DAS).

Results: Sole maize recorded highest dry matter (11938 kg ha^{-1})yield. Soil + foliar zinc application (Zn_2) recorded an increase of 37.93 % increase in dry matter yield over control (Zn_0). Maize + legumes recorded higher nitrogen uptake. There was an overall increase (122.34%) in zinc uptake from Zn_0 to Zn_2. Soil + foliar applied Zn increased ZnUE by 27.60 % (619.14 kg) over soil applied Zn (485.19 kg). Zn application increased Zn values of soil to 0.50 ppm with soil application and 0.56 ppm with soil + foliar application from the initial value of 0.36 ppm.

Interpretation: Intercropping of legumes and application of 20 kg $ZnSO_4$ as basal soil application plus two foliar applications of 0.5% $ZnSO_4$ at 30 and 50 days after sowing significantly increased forage yield, nutrient uptake and enhanced soil zinc levels.

Key words: Cropping systems, Intercropping, Legumes, Nutrient dynamics, Yield, Zn fortification



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Introduction

Globally, forage cultivation from cereal + legume mixed cropping systems, can ensure equitable and judicious utilization of resources, increase forage biomass, resource utilization, and soil fertility and produce highly nutritive forage through improvements in protein content and rumen degradability (Zhang *et al.,* 2015; Manoj *et al.,* 2021; Luo *et al.,* 2023). Intercropping involving two distinct species, in addition to aboveground interactions, extend its influence on belowground interactions, impacting the availability of soil nutrients through processes like nutrient competition. This can also lead to the stimulation of beneficial soil microbes, releasing nutrients during mineralization of organic matter. Additionally, intercropping may facilitate the mobilization of sparingly soluble inorganic nutrients and transfer of nutrients through common mycorrhizal networks (Xue *et al.,* 2016). When integrated into forage-based cropping systems, legumes contribute to a more balanced nutrient profile, fostering a conducive environment for plant growth.

Nitrogen is a key nutrient that determines herbage yield and quality (Kashyap *et al.,* 2023) through its effect on protein and chlorophyll formation. Similarly, owing to their roles in plant growth and development, phosphorus and potassium improve fodder production and quality (Rehman *et al.,* 2022). Fortifying forage-based cropping systems with micronutrients such as zinc not only addresses potential nutrient deficiencies but also plays a vital role in enhancing crop quality (Bevis, 2015). Zinc, as an important nutrient for plants, also plays a critical role in quality fodder production (Mahdi *et al.,* 2012; Ramakrishna *et al.,* 2022). The role of zinc as a cofactor of enzymes and proteins involved in cell division, photosynthesis, hormone production, cellular growth, protein synthesis, differentiation and metabolism and extensive plant root system results in vigorous plant growth and better forage quality. Like other crops, lower levels of Zn cause a reduction of yield in fodder crops and a deficiency of zinc affects animal's health and milk production severely.

About 50% of Indian soils are deficient in Zn, causing lower levels of Zn and yield in fodder crops. In the Himalayan Kashmir region, Diethylenetriaminepenta-acetic acid (DTPA)-extractable Zn varies from 0.35 to 0.65 mg kg^{-1} at high altitude soils, while as benchmark soils of Kashmir valley are highly variable (0.15 to 1.00 mg kg^{-1}) in DTPA-extractable zinc (Jalali *et al.,* 1989; Kakar *et al.,* 2018). Direct linkages between available micronutrients in the soil and their contents in forage and fodders have been widely studied and clearly established (Nube and Voortman, 2006). Micronutrient bio-fortification, the process of enriching micronutrients including Zn in the edible parts and foliage of crops, represents a sustainable, economical and easily implementable solution to overcome micronutrient deficiencies (Bevis, 2015). While most studies on nutrient efficiency in cereal/legume intercropping systems focus on nitrogen, particularly in relation to N_2 fixation, the exploration of soil phosphorus, potassium and micronutrients like zinc remains limited. Recent attention has been directed towards this research field, with notable occurrences of enhanced soil phosphorus acquisition by cereals intercropped with legumes (Li *et al.,* 2007). Similarly, there have been reported instances of improved iron and zinc uptake by legume crops when intercropped with cereals (Zuo and Zhang, 2009). Recent studies on micronutrient biofortification have focused on the management practices in single-species cropping (Xue *et al.,* 2016), but less work has been done in intercropping systems. Biofortification, supplementation, and fortification of crops are successful ways to enhance crop quality worldwide but intercropping is a nature-based, cost-effective, and sustainable approach to alleviate micronutrient deficiency of plants (Ebbisa, 2022). Thus, the present study was conducted to evaluate the synergistic effects of cereal-legume intercropping and zinc fortification on forage yield, quality and their effects on plant and soil nutrient dynamics.

Materials and Methods

The field experiments were conducted during *kharif* seasons of 2020 and 2021 at ICAR-IGFRI, Regional Research Station, Srinagar located at 33° 59' 23.9" N latitude and 74° 48' 0.2"E longitude, 1650 m above mean sea level. The experiments were laid out in a Factorial Randomized Block Design with two factors and each treatment replicated thrice. Treatment combinations included five cropping systems i.e. sole maize, sole cowpea, sole soybean, maize + cowpea (2:1), maize + soybean (2:1) and three zinc levels; Zn_0= control or no zinc application, Zn_1 = 20 kg $ZnSO_4$ ha^{-1} (basal soil application) and Zn_2 = 20 kg $ZnSO_4$ ha^{-1} (basal soil application) + 0.5% $ZnSO_4$ spray twice (30 DAS and 50 DAS). The soil of the experimental plot was sandy clay-loam in texture with pH 6.9, organic carbon 0.72 %, bulk density 1.23 Mg m^{-3} and electrical conductivity 0.28 dS m^{-1}, medium available nitrogen (295 kg ha^{-1}) and available phosphorus (16.7 kg ha^{-1}), high available potassium (364.5 kg ha^{-1}) and low zinc (0.36 ppm). Crops were raised with standard agronomic practices. The total rainfall received during the period of crop growth (April to July) was 29.49 cm and 58.07 cm during 2020 and 2021, respectively. The minimum temperature ranged from 6.21 to 17.00 ^{0}C during 2020 and 5.60 to 19.99 ^{0}C during 2021; maximum temperature ranged from 19.21 to 33.21 ^{0}C and 17.07 to 33.29 ^{0}C during 2020 and 2021, respectively. The crops were harvested 85 DAS. Plant samples from each treatment were collected at harvest, oven dried at 60-65 ±5 ^{0}C to a constant weight, powdered and used for various analyses. All the oven dried samples were ground in Willey mill using 2 mm sieve. In case of intercropping systems, the plant samples were mixed as per the row proportion (maize: legume = 2:1) adopted in the study.

Nutrient estimation of plant samples: Nitrogen content was estimated by digesting 0.5 g sample with 10 ml concentrated sulphuric acid and digestion mixture (K_2SO_4 + $FeSO_4$ + $CuSO_4$ in the ratio of 20:2:1) by using micro Kjeldahl method (Singh and Praharaj, 2017). Phosphorus content was determined by Vanado-molybdo phosphoric acid yellow colour method using spectrophotometer by digestion in Di-acid mixture (HNO_3: $HClO_4$ in the ratio of 9:4) (Singh and Praharaj, 2017). Potassium content

was determined by Extraction with Ammonium acetate and flame photometery (Jackson, 1973). Zinc content was determined by using Di-acid (HNO_3:$HClO_4$ in 9:4 ratio) digest on an Atomic Absorption Spectrophotometer and expressed in parts per million (Lindsay and Norvell, 1978; Prasad *et al.,* 2006). Nutrient uptake was calculated by multiplying dry matter production with corresponding nutrient content and was expressed as kg ha^{-1} and g ha^{-1} (in case of zinc).

Efficiency indices: The agronomic zinc-use efficiency (ZnUE) and apparent Zn recovery were calculated from the data on yield, Zn applied and Zn uptake as per the following formulae:

$$\text{ZnUE (kg kg}^{-1}\text{ Zn applied)} = \frac{\text{[Yield from fertilized plot – Yield from control plot]}}{\text{Amount of Zn fertilizer applied}}$$

$$\text{Apparent Zn Recovery (\%)} = \frac{\text{[Uptake of Zn in treated plot – Uptake of Zn in control plot]} \times 100}{\text{Amount of Zn fertilizer applied (g Zn ha}^{-1}\text{)}}$$

Soil physico-chemical properties: Soil samples from representative sites of each experimental plot were drawn (up to 15 cm depth) at the beginning and immediately after harvesting the crops. Each sample was thoroughly mixed, air-dried, and grinded with pestle and mortar and passed through a 2 mm mesh sieve. The samples were analyzed for pH, EC (Jackson, 1973), available N (Subbiah and Asija, 1956), P (Olsen *et al.,* 1954), K (Jackson, 1973) and Zn (Lindsay and Norvell, 1978) by standard procedures. Further organic carbon (Walkley and Back rapid titration, Jackson, 1973) and bulk density (Chopra and Kanwar, 2008) were analyzed for soil samples obtained from a depth of 0-30 cm and soil carbon stock of upper 30 cm thick layer was calculated by the following formula (Dar and Somaiah, 2015) :

Soil carbon stock (kg ha^{-1}) = organic carbon (%) × bulk density × soil depth/thickness ×1000

Statistical analysis: The statistical analysis of data of various parameters obtained during investigation was carried out through the procedure appropriate to the design of the experiment as described by Snedecor and Cochran (1967).Significance of the treatments were tested using F test with 5% level of significance (P<0.05) and means were compared using least significant difference test.

Results and Discussion

Among the cropping systems, sole maize recorded highest green fodder (45574 kg ha^{-1}) and dry matter (11938 kg ha^{-1}) yield followed by maize + soybean intercropping which recorded 42904 kg ha^{-1} and 10861 kg ha^{-1} green and dry matter yield, respectively (Table 1). Zinc fertilization significantly increased fodder yield of all cropping systems. Zn_2 treatment recorded a yield increase of 9.69 % in green and 37.93 % increase in dry matter yield over control (Zn_0). Higher forage yield with sole planting of maize may be attributed to higher biomass in maize and higher habitation population (3,33,333 plants ha^{-1}) of maize in sole planting compared to lower plant population of maize (2,22,222 plants ha^{-1}) in replacement series of intercropping. The variation in total biomass production is due to crop compatibility, genetic makeup of crop and above and below ground interaction of crop for sharing of nutrients, water, light and space (Kumhar *et al.,* 2022). Baghdadi *et al.* (2016) reported higher dry matter yield of corn monocrop (14.77 t ha^{-1}) and lower in corn intercropped with soybean at different ratios. Kumhar *et al.* (2022) found that sole planting of pearl millet hybrid recorded 160.8 and 40.2 t ha^{-1} green and dry fodder yields which were significantly higher than all the grass-legume combinations.

Zn_2 treatment recorded a yield increase of 9.69 % in green and 37.93 % in dry matter over control or no zinc application. The favourable impact of zinc resulted in taller plants through internode elongation, increased leaf area and dry matter production and hence higher fodder yield. The beneficial role of zinc on higher biomass production might be attributed to synthesis of tryptophan in plants, a precursor for the production of growth regulators like auxin, indole acetic acid, and cytokinin which play a significant role in cell division, cell elongation and root growth thereby, enhancing the growth attributes and nutrient uptake by crop with consequent increase in vegetative growth (Suganya *et al.,* 2020). In addition to soil application, foliar application of zinc enhances photosynthesis and formation of auxin and leads to rapid growth rate (Ramakrishna *et al.,* 2022). Kumar and Ram (2021) reported 25% increase in maize fodder yield over control with soil application ($ZnSO_4$ @ 16 kg ha^{-1}) plus two foliar sprays of $ZnSO_4$ @ 0.3 % at 30 and 40 days after sowing over control. Ahmad *et al.* (2018) observed that application of 10 kg ha^{-1} zinc along with 120 kg ha^{-1} nitrogen to fodder sorghum showed an average increase of 12.95 % in green fodder yield and 13.95 % in dry matter yield over control.

Among different cropping systems, sole legumes (cowpea and soybean) recorded significantly higher nitrogen (2.21 and 2.12 %) and potassium (2.84 and 2.85 %) contents whereas sole maize recorded highest phosphorus (1.45 %) and zinc (43.00 ppm) contents. Intercropping of maize with legumes improved nutrient contents over monocrop systems. With respect to nutrient uptake, maize + soybean recorded highest nitrogen (193.06 kg ha^{-1}) and potassium (235.06 ha^{-1}) uptake whereas sole maize recorded highest phosphorus (54.67 ha^{-1}) and zinc (523.51 g ha^{-1}) uptake. Legumes in sole planting recorded lowest nutrient uptakes. Intercropping of maize with both the legumes improved nitrogen content and uptake significantly over sole maize. Higher nitrogen uptake with maize + soybean intercropping was due to higher dry matter yield than sole legumes and higher nitrogen content than sole maize. When cereals and legumes are grown in association in an intercropping system, the nitrogen nutrition of

Table 1: Effect of different cropping systems and zinc levels on forage yield and nutrient uptake

Treatments	GFY (kg ha^{-1})	DMY (kg ha^{-1})	N content (%)	N uptake (kg ha^{-1})	P content (%)	P uptake (kg ha^{-1})	K content (%)	K uptake (kg ha^{-1})	Zn content (ppm)	Zn uptake (kg ha^{-1})
Maize	45574	11938	1.46	175.16	0.45	54.67	1.91	229.59	43.00	523.51
Cowpea	22466	4633	2.21	102.89	0.31	14.69	2.84	132.22	38.61	185.53
Soybean	25582	5698	2.12	121.09	0.32	18.50	2.85	163.05	37.62	222.93
Maize + Cowpea	41182	10310	1.83	190.01	0.41	43.17	2.18	225.28	40.02	423.07
Maize + Soybean	42904	10861	1.77	193.06	0.40	44.57	2.15	235.06	40.22	447.34
SE(m) ±	191.43	175.77	0.01	3.25	0.01	1.21	0.02	4.86	1.17	15.31
C.D. ($p \leq 0.05$)	557.43	511.83	0.03	9.48	0.03	3.53	0.06	14.15	3.43	44.58
Zinc										
Zn_0	33716	7213	1.85	126.46	0.37	28.69	2.36	160.01	29.63	216.16
Zn_1	35925	8903	1.88	160.38	0.39	36.62	2.39	202.13	42.43	384.64
Zn_2	36984	9949	1.90	182.49	0.38	40.05	2.41	228.99	47.62	480.63
SE(m) ±	148.28	136.15	0.009	2.52	0.008	0.93	0.01	3.76	0.91	11.85
C.D. ($p \leq 0.05$)	431.78	396.46	0.026	7.34	NS	2.73	NS	10.96	2.65	34.53
CS × Zn										
C.D. ($p \leq 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS	77.21

Table 2: Interaction effect between cropping systems andzinc levels with respect to zinc uptake

CS × Zn	Zn_0	Zn_1	Zn_2
Maize	319.35	563.15	688.03
Cowpea	98.38	189.60	268.63
Soybean	123.70	236.20	308.90
Maize + Cowpea	263.88	446.37	558.95
Maize + Soybean	275.49	487.87	578.66
SE(m) ±		26.51	
C.D. ($p \leq 0.05$)		77.21	

the associated cereal is improved due to transfer of biologically fixed nitrogen from associated legume (Layek *et al.,* 2018). Phosphorus and potassium concentration in legume forages is generally slightly higher or similar to grasses (Paulson *et al.,* 2008), however, in the present study sole maize recorded higher phosphorus content. Phosphorus availability in mixed-crop rhizosphere is increased by secretion of organic exudates and also by the release of protons. It is also well known that legumes have higher potassium absorption efficiency than grasses. Root exudates containing glutamic acid, tyrosine and leucine increase potassium uptake from the soil (Wei *et al.,* 2022) which suggests that legumes can compensate for lower potassium levels in neighbouring grasses. Fan *et al.* (2020) reported higher N, P, K uptake with maize-soybean intercropping compared to sole planting of maize and soybean. Nasar *et al.* (2022) found that maize + alfalfa intercropping increased N, P and K contents both in maize and alfalfa compared with their mono-cropping. The higher uptake of zinc in maize based systems could be due to release of phytosiderophores by Poaceae (maize) species which can chelate zinc and increase its uptake by plants. Dragicevic *et al.* (2015) reported higher zinc and iron concentration in maize compared to soybean. Nasar *et al.* (2022) reported that intercropping of alfalfa with maize increased zinc content of alfalfa under both pot and field conditions. As the total nutrient uptake by a plant is a function of dry matter production and nutrient concentration at harvesting. Hence, the present investigation also reported higher nutrient uptake (N, P, K and Zn) with highly productive systems, *i.e.,* sole maize and maize + soybean.

Application of zinc significantly enhanced nutrient contents and uptake. Zn_2 recorded significantly higher nitrogen content (1.90 %) and uptake (182.49 kg ha^{-1}) over Zn_1 (160.38 kg ha^{-1}) and Zn_0 (126.46 kg ha^{-1}). Zinc fertilization had no significant effect on plant phosphorus content, however, phosphorus uptake increased significantly over Zn_0 (control). Zinc fertilization improved K content from 2.36 % (Zn_0) to 2.41 % (Zn_2), and also increased K uptake from 160.01 kg ha^{-1} (Zn_0) to 228.99 kg ha^{-1} (Zn_2). Increased uptake of N, P and K may be due to synergistic effect of zinc on nutrient uptake and increased dry matter production. Kumar *et al.* (2016) reported increase in N and P uptake in fodder cowpea with soil application of $ZnSO_4$ up to 20 kg ha^{-1}. Amutham *et al.* (2021) reported higher uptake of NPK and Zn in baby corn with zinc fertilization. There was a significant increase in zinc content (29.63 ppm to 47.62 ppm) and zinc uptake (216.16 g ha^{-1} to 480.63 g ha^{-1}) with zinc application.

The increased Zn yield in response to zinc application may be due to increased availability in the rhizosphere, efficient foliar uptake with minimal losses and increased dry matter yield. In addition to soil application, foliar sprays resulted in better translocation of nutrient within the plant system leading to increased plant zinc concentration by 60.71 % and uptake by 122.34 % over control. Kumar *et al.* (2017) reported 45.53 % higher zinc content and 103.63 % higher zinc uptake over control in fodder maize with $ZnSO_4$ at 20 kg ha^{-1}. Cropping systems and zinc fertilization had a

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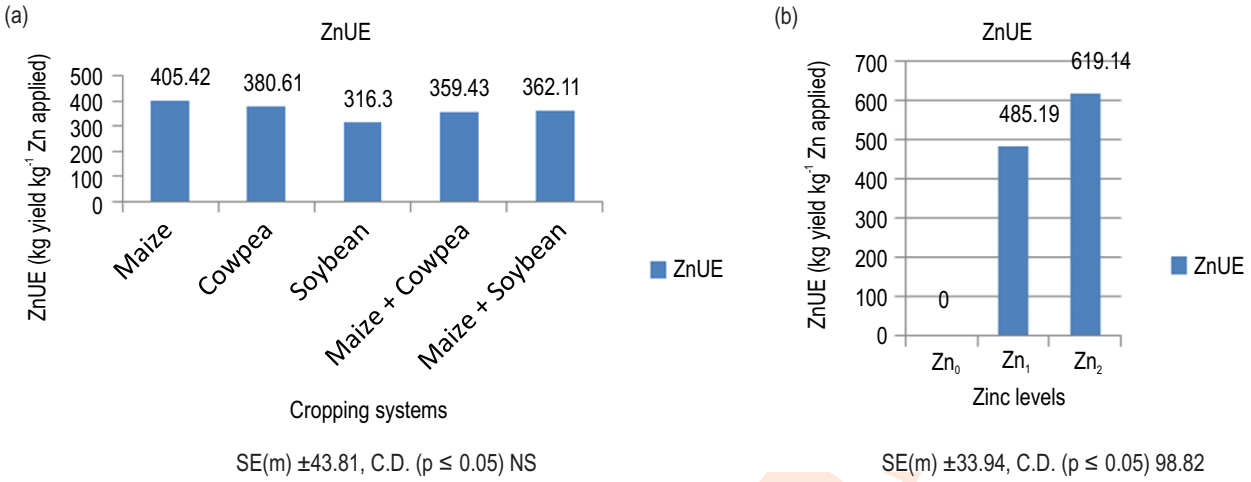

Fig. 1: Effect of different cropping systems (a) and zinc levels (b) on Zn use efficiency.

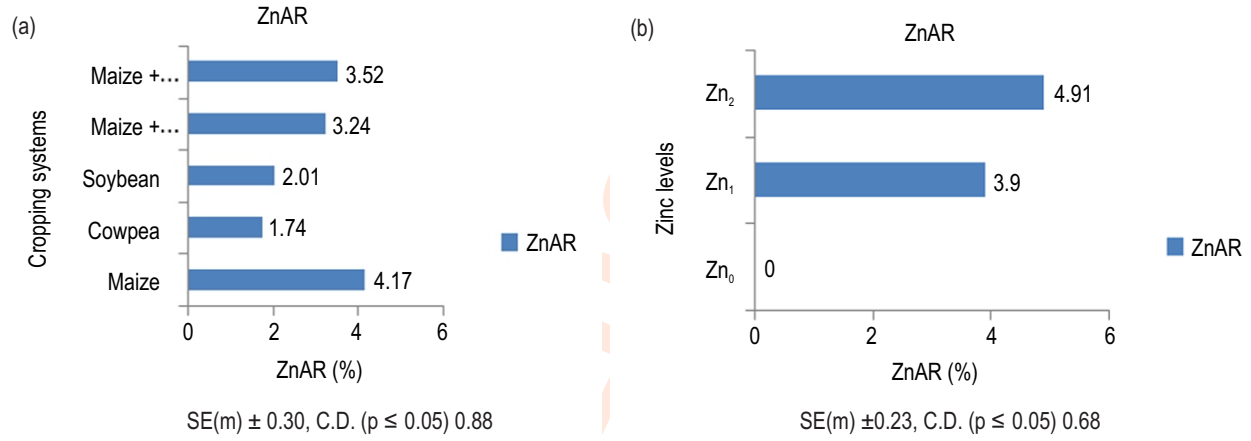

Fig. 2: Effect of different cropping systems (a) and zinc levels (b) on apparent recovery of Zn.

significant interaction for zinc uptake (Table 2).

The agronomic ZnUE varied from 316.30 kg (soybean) to 405.42 kg (maize). With soil application of 20 kg $ZnSO_4$ agronomic ZnUE of 485.19 kg was recorded which increased to 619.14 kg upon application of 20 kg $ZnSO_4$ (Zn_1) along with two foliar sprays of 0.5% $ZnSO_4$ solution (Zn_2). The maximum value of apparent recovery of zinc (4.17 %) was recorded in sole maize and lower values were recorded in cowpea (1.74 %) and soybean (2.01 %). Zn application increased apparent recovery percentage to 3.90 % with Zn_1 soil application and up to 4.91 % with Zn_2 soil + foliar application (Fig. 1, 2). Intercropping also increased apparent zinc recovery significantly over sole legume treatments. The yield improvement over unit quantity of Zn addition was calculated as Zn use efficiency. Soil + foliar applied Zn increased ZnUE by 27.60% over soil application only. The increased use efficiency with foliar application is because foliar application is an efficient method as nutrients are easily absorbed through leaf epidermis and remobilized further. Kumari (2017) reported ZnUE of 233 kg and apparent recovery of 1.9 % in berseem with zinc application @ 6 kg ha^{-1}. Rattan *et al.* (2008) reported an average response of 670 kg in maize. Higher response to zinc application in maize may be due to higher zinc and dry matter contents in maize crop.

Soil pH, EC and bulk density did not vary much with the cropping systems and remained almost similar to their initial values. Zinc application had no significant influence on these parameters. Organic carbon content varied significantly among different treatments. Maize + legume intercropping recorded higher organic carbon content (0.74 %) over sole maize and sole legume treatments. The two intercropped treatments also improved

Table 3: Effect of different cropping systems and zinc levels on physico-chemical properties and soil nutrient availability

Treatments	pH	EC ($ds\ m^{-1}$)	B.D ($Mg\ m^{-3}$)	O.C (%)	Soil C stock ($kg\ ha^{-1}$)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)	Zn (ppm)
Cropping system									
Maize	6.92	0.28	1.24	0.71	26756	274.29	16.31	353.88	0.41
Cowpea	6.87	0.26	1.22	0.72	27090	305.52	16.54	360.03	0.51
Soybean	6.87	0.25	1.23	0.72	27155	307.13	16.45	358.59	0.48
Maize + Cowpea	6.90	0.25	1.23	0.74	28108	284.25	16.33	358.40	0.44
Maize + Soybean	6.91	0.26	1.24	0.74	28210	286.78	16.31	357.00	0.43
SE(m) ±	0.01	0.01	0.01	0.01	407.49	1.18	0.33	1.25	0.01
C.D. ($p \leq 0.05$)	NS	NS	NS	0.02	1163.41	3.41	NS	3.76	0.02
Zinc									
Zn_0	6.87	0.26	1.24	0.71	26513	296.96	16.40	359.33	0.33
Zn_1	6.88	0.26	1.23	0.73	26842	288.99	16.31	357.25	0.50
Zn_2	6.87	0.27	1.23	0.73	27243	286.76	16.12	356.74	0.56
SE(m) ±	0.01	0.01	0.01	0.01	316.23	0.91	0.25	0.75	0.01
C.D. ($p \leq 0.05$)	NS	NS	NS	NS	NS	2.65	NS	NS	0.02

organic carbon content from the initial value of 0.72 %. Soil carbon stock was also significantly influenced by cropping systems. The highest soil carbon stock was recorded in maize + soybean intercropping (28210 kg ha^{-1}). Zinc fertilization had no significant influence on OC content or soil carbon stock. However, soil carbon stock increased with zinc application from 26513 kg ha^{-1} in Zn_0 to 27243 kg ha^{-1} in Zn_2 treatments. Sole legume plots recorded slightly lower soil pH, EC and bulk density after crop harvesting. Lower pH after legume cultivation may be attributed to the fact that legumes obtain much of their nitrogen from air rather than soil as NO_3. On the other hand, non-legumes release OH^- ions into rhizosphere in exchange of NO_3 and hence, the net result is increase in soil pH. Lower bulk density after legume cultivation may be due to narrow C: N ratios of legume residues leading to their fast decomposition and improved soil organic matter, thereby, improving soil aggregation and decreasing its bulk density (Layek *et al.,* 2018).

Intercropping of maize with legumes improved soil carbon stock over sole maize and sole legume treatments. Increased soil organic carbon contents in intercropped treatments (at low legume proportions) could be due to increased primary productivity, low C/N ratios of legume residues and inhibition of oxidative enzymes to degrade more recalcitrant compounds and hence, reduced CO_2 emissions and C losses (Rodriguez *et al.,* 2022). Grass + legume intercropping significantly increased carbon stock over sole grass treatments. Zinc fertilization had no significant influence on the organic carbon and soil carbon stock. However, organic carbon and soil carbon stock increased in response to zinc application due to higher plant growth. Soil available nitrogen varied significantly with the cropping systems and was found highest with sole soybean recording (307.13 kg ha^{-1}) recording an improvement over the initial value (295.7 kg ha^{-1}). Sole maize recorded lowest available nitrogen (274.29 kg ha^{-1}). The highest available nitrogen was recorded with Zn_0 (296.96 kg ha^{-1}), which was significantly higher over Zn_1 (288.99 kg ha^{-1}) and Zn_2 (286.76 kg ha^{-1}), respectively. Soil available phosphorus did not differ significantly with cropping systems. Zinc application reduced phosphorus availability; however, the differences were non-significant. Soil available potassium was found highest with sole cowpea (360.03 ha^{-1}) and lowest insole maize (353.88 kg ha^{-1}). Application of zinc had no significant influence on available potassium. Available zinc was recorded highest in sole cowpea (0.51 ppm) followed by sole soybean (0.48 ppm) and lowest in sole maize (0.41 ppm). Intercropping resulted in lesser depletion of soil zinc as compared to maize monocropping. Application of zinc increased available zinc with successive applications. Zn_2 treatment recorded significantly higher available Zn of 0.56 ppm registering an increase of 69.69 %in zinc availability over control (Zn0). Both Zn1 (0.50 ppm) and Zn2 (0.56 ppm) recorded an increase in soil available zinc over initial value of 0.36 ppm (Table 3).

The variation in nutrient availability among different cropping systems may be due to differential nutrient mining of fodder crops. Sole maize because of its high biomass producing potential and exhaustive nature, resulted in higher NPK and Zn uptake and hence, lower soil availability. Moreover, higher available N in sole legume treatments might be due to the fact that leguminous crops have the ability to fix atmospheric nitrogen as a result of which nitrogen balance of the soil increased. Legume based intercropping systems improve several aspects of soil fertility, namely soil organic matter, and humus content along with N and P availability (Jensen *et al.,* 2012). Maize monocropping resulted in highest nutrient uptake and lowest soil availability after harvesting as compared to intercropping with cowpea (Vesterager *et al.,* 2008; Hindoriya *et al.,* 2019) and alfalfa (Nasar *et al.,* 2022).

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Application of zinc inversely affected available N, P and K contents but increased Zn content in the soil. Soil (Zn_1) and soil + foliar application of zinc (Zn_2) recorded an increase in zinc availability over initial zinc value of 0.36 ppm. The decrease in N, P and K contents with successive increase in zinc application may be due to higher biomass production and higher nutrient uptake in these treatments. Any management practice such as type of crop/system and fertilization strategy that enhances crop productivity also results in higher nutrient mining from the soils in order to achieve higher production targets. Prajapati *et al*. (2023) reported higher available nitrogen and available phosphorus in control (no zinc) treatment. However, lower available nitrogen and phosphorus and higher available zinc was recorded in zinc applied treatments. Xu *et al.* (2024) found that available nitrogen and phosphorus in soil were lower under high producing Italian rye grass and higher under less yielding legume forages. Soil zinc status in response to zinc application was improved because of lower initial status of zinc and increase in soil solution zinc concentration. Soil application is the easiest way of enhancing soil zinc levels. Kumar *et al.* (2016) reported that zinc content increased from 0.43 ppm in control (no zinc) to 0.73 ppm when zinc was applied as ZnSO @ 40 kg ha^{-1} to fodder cowpea. Peddapuli *et al.* (2021) reported that zinc application in sweet corn registered significant (0.77 ppm) increase in available zinc in soil after harvesting over control (0.37 ppm).

The integration of legumes and zinc fortification in forage cropping systems presents a holistic approach for farmers aiming to enhance soil health, forage yield and quality. This study recommends the inclusion of legumes and application of 20 kg $ZnSO_4$ as a basal soil treatment, coupled with two foliar applications of 0.5% $ZnSO_4$ at 30 and 50 days after sowing in forage-based cropping systems to boost forage yield, quality, nutrient uptake and increased soil zinc levels.

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