



Effect of integrated nutrient management on soil enzymatic activities in a maize–groundnut cropping system in Alfisols

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ABSTRACT

Soil enzyme activity is a sensitive indicator of soil biological health and nutrient cycling, making it an important parameter for evaluating sustainable nutrient management practices. A field experiment was conducted during 2019–20 and 2020–21 at S.V. Agricultural College, Tirupati, Andhra Pradesh, to assess the effect of integrated nutrient management (INM) practices on soil enzymatic activities in a maize–groundnut cropping system. The experiment was laid out in a split-plot design with three fertilizer levels (125%, 100%, and 75% recommended dose of fertilizers (RDF)) as main plots and four nutrient management practices comprising control, farmyard manure (FYM @ 10 t ha⁻¹), poultry manure (@ 5 t ha⁻¹), and urban compost (@ 5 t ha⁻¹) as subplots. The combined application of organic and inorganic nutrient sources significantly enhanced urease, dehydrogenase, acid phosphatase, and alkaline phosphatase activities compared with the control. Among the organic sources, FYM consistently recorded the highest enzyme activities at tasselling and harvest stages of maize and at flowering and harvest stages of groundnut. Its superior performance was attributed to gradual nutrient release, improved soil organic carbon status, and favorable conditions for enzyme synthesis and nutrient transformation. Poultry manure also performed comparably and was superior to urban compost. Enzyme activities were generally higher during active crop growth stages and declined towards harvest. The study highlights that integration of FYM with recommended fertilizer doses is an effective strategy for improving soil biological functioning and sustaining soil health in maize–groundnut cropping systems.

Keywords: Integrated nutrient management, Soil enzymes, Urease, Dehydrogenase, Phosphatase, Farmyard manure, Maize-groundnut system, Soil health, Sustainable agriculture

INTRODUCTION

Soil enzymes are widely recognized as sensitive indicators of soil biological activity and play a fundamental role in nutrient cycling, organic matter decomposition, and soil fertility. Among the various enzymes present in soil, urease, dehydrogenase, acid phosphatase, and alkaline phosphatase are of

particular importance because they are directly involved in key biochemical processes governing nutrient transformation. Urease catalyzes the hydrolysis of urea into ammonium, thereby contributing to nitrogen mineralization, whereas dehydrogenase reflects the overall oxidative activity of soil microorganisms and serves as an indicator of microbial metabolic functioning (Laxminarayan,

2023; Bana *et al.*, 2022). Acid and alkaline phosphatases play a crucial role in phosphorus cycling by hydrolyzing organic phosphorus compounds into plant-available inorganic forms. Owing to their close association with nutrient cycling and microbial processes, soil enzyme activities are widely used as reliable indicators of soil health, fertility status, and sustainability under different agricultural management systems (Nannipieri *et al.*, 2017).

INM, which involves the combined use of organic and inorganic nutrient sources, has emerged as an effective strategy for sustaining soil productivity while maintaining environmental quality. Organic amendments such as farmyard manure (FYM), poultry manure, and urban compost not only supply essential nutrients but also improve soil organic carbon content, enhance soil structure, and create favorable conditions for enzymatic activity and nutrient transformations (Diacono and Montemurro, 2010). These organic inputs provide readily available carbon substrates and energy sources that stimulate biochemical processes in soil and promote enzyme-mediated nutrient cycling. Furthermore, the integration of organic and inorganic nutrient sources has been shown to improve nutrient use efficiency and maintain long-term soil productivity. The maize-groundnut cropping system is widely adopted in tropical and semi-arid regions because of its economic importance and complementary nutrient dynamics. Maize is a nutrient-demanding cereal crop that requires substantial external nutrient inputs, while groundnut contributes to improved soil fertility through biological nitrogen fixation (Bana *et al.*, 2022). However, continuous cultivation without balanced nutrient management may adversely affect soil biological processes and reduce nutrient-use efficiency (Zhang *et al.*, 2015). Several studies have demonstrated that the incorporation of organic nutrient sources within INM practices can enhance soil enzymatic activity and nutrient availability in cereal-legume cropping systems (Gupta *et al.*, 2025). In India, recent investigations have also highlighted the beneficial effects of integrated nutrient management on soil biological properties and crop productivity under diversified cropping systems (Krishan *et al.*, 2025; Gasal *et al.*, 2025).

Although the positive influence of INM on soil health has been widely reported, information regarding the comparative effectiveness of different

organic nutrient sources, particularly FYM, poultry manure, and urban compost, on urease, dehydrogenase, acid phosphatase, and alkaline phosphatase activities at different crop growth stages in maize-groundnut cropping systems remains limited. Understanding the response of these key enzymes to nutrient management practices is essential for developing sustainable nutrient management strategies that enhance nutrient cycling, improve soil fertility, and maintain long-term productivity.

Therefore, the present study was undertaken to evaluate the effect of different fertilizer levels and organic nutrient sources under integrated nutrient management on urease, dehydrogenase, acid phosphatase, and alkaline phosphatase activities at critical growth stages of a maize-groundnut cropping system.

MATERIALS AND METHODS

Experimental Site

A field experiment was conducted for two consecutive years (2019–20 and 2020–21) at Field No. 50B of the Wetland Farm, S.V. Agricultural College, Tirupati, Andhra Pradesh, India. The experimental site is geographically located at 13.5° N latitude and 79.5° E longitude, with an altitude of 182.9 m above mean sea level. The region falls under the Southern Agro-Climatic Zone of Andhra Pradesh and is classified as Semi-Arid Tropics (SAT) according to Troll's climatic classification.

Prior to the initiation of the experiment, composite surface soil samples (0–15 cm depth) were collected and analyzed for their physico-chemical properties. The experimental soil was classified as an Alfisol with a sandy clay loam texture, neutral to slightly alkaline in reaction, non-saline in nature, and medium in organic carbon and available nutrient status.

Experimental Design and Crop Management

The experiment was laid out in a split-plot design with three replications. Three fertilizer levels, viz., 125%, 100%, and 75% of the recommended dose of fertilizers (RDF), were assigned to the main plots, while four nutrient management practices comprising control, farmyard manure (FYM) @ 10 t ha⁻¹, poultry manure @ 5 t ha⁻¹, and urban compost @ 5 t ha⁻¹ were allotted to the subplots.

The main plot size was 6.0 m × 4.0 m, while the subplot size was 2.4 m × 2.5 m. Maize hybrid 'Kaveri-55K' was grown during the kharif season followed by groundnut variety 'K-6' during the rabi season in both years. The recommended fertilizer dose for maize was 180–60–40 kg N₂P₂O₅, and K₂O ha⁻¹, respectively, whereas for groundnut it was 20–30–50 kg N₂P₂O₅, and K₂O ha⁻¹, respectively. Organic manures were incorporated into the soil before sowing according to the treatment schedule, while inorganic fertilizers were applied as per crop recommendations.

Soil Sampling and Processing

Soil samples were collected from each treatment plot at critical growth stages of maize (tasselling and harvest) and groundnut (flowering and harvest). Composite soil samples were obtained by collecting multiple cores from the rhizosphere zone of each plot and thoroughly mixing them.

Fresh soil samples were stored at 4°C and used for enzyme activity analysis. Samples intended for other analyses were air-dried under shade, gently crushed, and passed through a 2-mm sieve.

Determination of Soil Enzyme Activities

Urease Activity

Soil urease activity was determined following the method of Tabatabai and Bremner, (1972). Soil samples were incubated with urea solution in tris (hydroxymethyl) aminomethane (THAM) buffer, and the ammonium nitrogen (NH₄⁺-N) released through urea hydrolysis was quantified spectrophotometrically. Urease activity was expressed as µg NH₄⁺-N g⁻¹ soil h⁻¹.

Dehydrogenase Activity

Dehydrogenase activity was estimated using the procedure described by Casida *et al.* (1964). The method is based on the reduction of 2,3,5-triphenyl tetrazolium chloride (TTC) to triphenyl formazan (TPF) by microbial oxidative enzymes present in soil. The intensity of the red-colored TPF formed was measured spectrophotometrically and expressed as µg TPF g⁻¹ soil h⁻¹.

Acid and Alkaline Phosphatase Activities

Acid phosphatase and alkaline phosphatase activities were determined following the method of

Tabatabai and Bremner, (1972). Soil samples were incubated with p-nitrophenyl phosphate (PNPP) substrate under acidic and alkaline buffer conditions, respectively. The p-nitrophenol (PNP) released during enzymatic hydrolysis was measured spectrophotometrically, and enzyme activity was expressed as µg PNP g⁻¹ soil h⁻¹.

Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a split-plot design following the procedure outlined by Gomez and Gomez, (1984). Treatment means were compared using the Critical Difference (CD) test at the 5% level of significance ($P \leq 0.05$). Wherever treatment effects were non-significant, the results were denoted as NS (non-significant). Pooled analysis across the two years was also carried out to assess the consistency of treatment effects over time.

RESULTS AND DISCUSSION

Effect of Integrated Nutrient Management on Soil Enzyme Activities in Maize

INM significantly influenced soil enzyme activities at both tasseling and harvest stages of maize (Table 1 and 2; Fig. 1 and 2). The pooled data showed that urease, dehydrogenase, acid phosphatase and alkaline phosphatase activities increased with increasing fertilizer levels, with 125% RDF consistently recording higher values than 100% and 75% RDF. Adequate nutrient availability under higher fertilizer levels promotes root growth and rhizosphere activity, thereby stimulating microbial processes and enzyme production, as reported by Krishna *et al.* (2025) and Ghasal *et al.* (2025).

Enzyme activities were generally higher at tasseling than at harvest. The decline in enzymatic activity observed at harvest may be attributed to reduced root exudation and lower availability of easily decomposable carbon substrates as the crop approaches physiological maturity. According to Nannipieri *et al.* (2017), soil enzyme activities are strongly regulated by microbial activity and substrate availability in the rhizosphere. Under 125% RDF, urease activity declined from 150.61 to 131.80 µg NH₄⁺-N g⁻¹ h⁻¹, while dehydrogenase activity decreased from 94.3 to 84.4 µg TPF g⁻¹ h⁻¹, indicating reduced microbial metabolic activity during the later stages of crop growth (Bana *et al.*, 2022).

Table 1. Influence of integrated nutrient management on soil enzyme activities at the tasseling stage of maize

Treatments	Urease ($\mu\text{g NH}_4^+ \text{ N g}^{-1} \text{ h}^{-1}$)			Dehydrogenase ($\mu\text{g of TPF g}^{-1} \text{ h}^{-1}$)			Acid phosphatase ($\mu\text{g PNP g}^{-1} \text{ h}^{-1}$)			Alkaline phosphatase ($\mu\text{g PNP g}^{-1} \text{ h}^{-1}$)		
	2019	2020	pooled	2019	2020	pooled	2019	2020	pooled	2019	2020	pooled
Main plots												
M ₁ = 125 % RDF	145.60	153.94	150.61	94.8	93.8	94.3	82.4	85.1	83.7	83.8	87.6	85.7
M ₂ = 100 % RDF	125.46	127.11	128.78	86.4	82.1	84.3	79.4	81.7	80.5	75.8	79.0	77.4
M ₃ = 75 % RDF	122.90	132.70	121.30	75.4	79.4	77.4	72.6	73.7	73.1	76.8	79.8	78.3
SEm+	2.11	1.29	1.33	0.63	0.40	0.50	0.49	0.36	0.40	0.25	0.25	0.24
CD (P=0.05)	8.28	5.08	5.20	2.49	1.57	1.95	1.91	1.40	1.56	0.96	0.96	0.93
Sub plots												
S ₁ = Control	61.59	65.02	65.53	53.4	43.0	48.2	45.6	48.7	47.2	55.8	59.8	57.8
S ₂ = FYM @ 10 tonnes ha ⁻¹	165.10	173.58	158.68	97.6	100.9	99.2	92.4	92.7	92.5	91.4	94.4	92.9
S ₃ = Poultry manure @ 5 tonnes ha ⁻¹	145.79	150.76	151.38	98.7	103.8	101.2	89.6	92.2	90.9	85.8	89.1	87.5
S ₄ = Urban compost @ 5 tonnes ha ⁻¹	152.78	162.32	158.66	92.6	92.6	92.6	84.9	87.0	86.0	82.2	85.2	83.7
SEm+	2.70	2.17	1.95	0.90	0.42	0.36	0.42	0.46	0.38	0.39	0.41	0.39
CD (P=0.05)	8.03	6.45	5.78	2.68	1.24	1.06	1.26	1.35	1.14	1.17	1.22	1.16
Interaction												
Sub at same level main (S × M)												
SEm+	8.11	6.52	5.84	2.70	1.25	1.07	1.27	1.37	1.15	1.18	1.23	1.17
CD (P=0.05)	NS	NS	NS	NS	4.32	3.70	4.41	4.73	3.98	4.09	4.26	4.05
Main at same or different level sub (M × S)												
SEm+	42.76	34.16	30.69	14.2	6.6	5.8	6.8	7.2	6.1	6.2	6.4	6.1
CD (P=0.05)	NS	NS	NS	NS	21.9	20.2	23.1	23.3	20.5	19.5	20.2	19.3

Table 2. Influence of integrated nutrient management on soil enzyme activities at the harvesting stage of maize

Treatments	Urease ($\mu\text{g NH}_4^+ \text{ N g}^{-1} \text{ h}^{-1}$)			Dehydrogenase ($\mu\text{g of TPF g}^{-1} \text{ h}^{-1}$)			Acid phosphatase ($\mu\text{g PNP g}^{-1} \text{ h}^{-1}$)			Alkaline phosphatase ($\mu\text{g PNP g}^{-1} \text{ h}^{-1}$)		
	2019	2020	pooled	2019	2020	pooled	2019	2020	pooled	2019	2020	pooled
Main plots												
M ₁ = 125 % RDF	129.4	134.2	131.8	74.9	93.8	84.4	46.6	50.5	48.6	56.8	60.0	58.4
M ₂ = 100 % RDF	123.6	125.9	124.7	65.1	85.6	75.4	40.0	43.1	41.6	50.7	53.9	52.3
M ₃ = 75 % RDF	116.0	119.2	117.6	64.4	81.6	73.0	33.0	36.1	34.5	35.7	38.9	37.3
SEm+	1.77	1.69	1.72	0.07	0.68	0.32	0.29	0.38	0.33	0.14	0.14	0.14
CD (P=0.05)	NS	NS	NS	0.27	2.66	1.27	1.13	1.49	1.29	0.55	0.55	0.55
Sub plots												
S ₁ = Control	86.4	86.2	86.3	40.0	42.6	41.3	25.6	32.3	29.0	27.1	30.3	28.7
S ₂ = FYM @ 10 tonnes ha ⁻¹	136.5	141.9	139.2	86.1	102.4	94.2	46.2	48.5	47.4	56.6	59.9	58.2
S ₃ = Poultry manure @ 5 tonnes ha ⁻¹	138.0	143.7	140.9	77.3	105.6	91.4	45.0	47.3	46.2	59.3	62.5	60.9
S ₄ = Urban compost @ 5 tonnes ha ⁻¹	131.2	133.7	132.5	69.1	97.7	83.4	42.6	44.8	43.7	48.0	51.2	49.6
SEm+	1.84	1.93	1.86	0.13	0.95	0.49	0.47	0.55	0.46	0.19	0.19	0.19
CD (P=0.05)	5.48	5.72	5.52	0.39	2.83	1.47	1.39	1.62	1.36	0.55	0.55	0.55
Interaction												
Sub at same level main (S × M)												
SEm+	5.53	5.78	5.58	0.39	2.86	1.48	1.41	1.64	1.37	0.56	0.56	0.56
CD (P=0.05)	NS	NS	NS	1.36	NS	5.13	NS	NS	4.74	1.92	1.92	1.92
Main at same or different level sub (M × S)												
SEm+	29.4	30.6	29.6	2.1	15.0	7.8	7.4	8.6	7.2	2.9	2.9	2.9
CD (P=0.05)	NS	NS	NS	6.4	NS	24.6	NS	NS	23.0	9.4	9.4	9.4

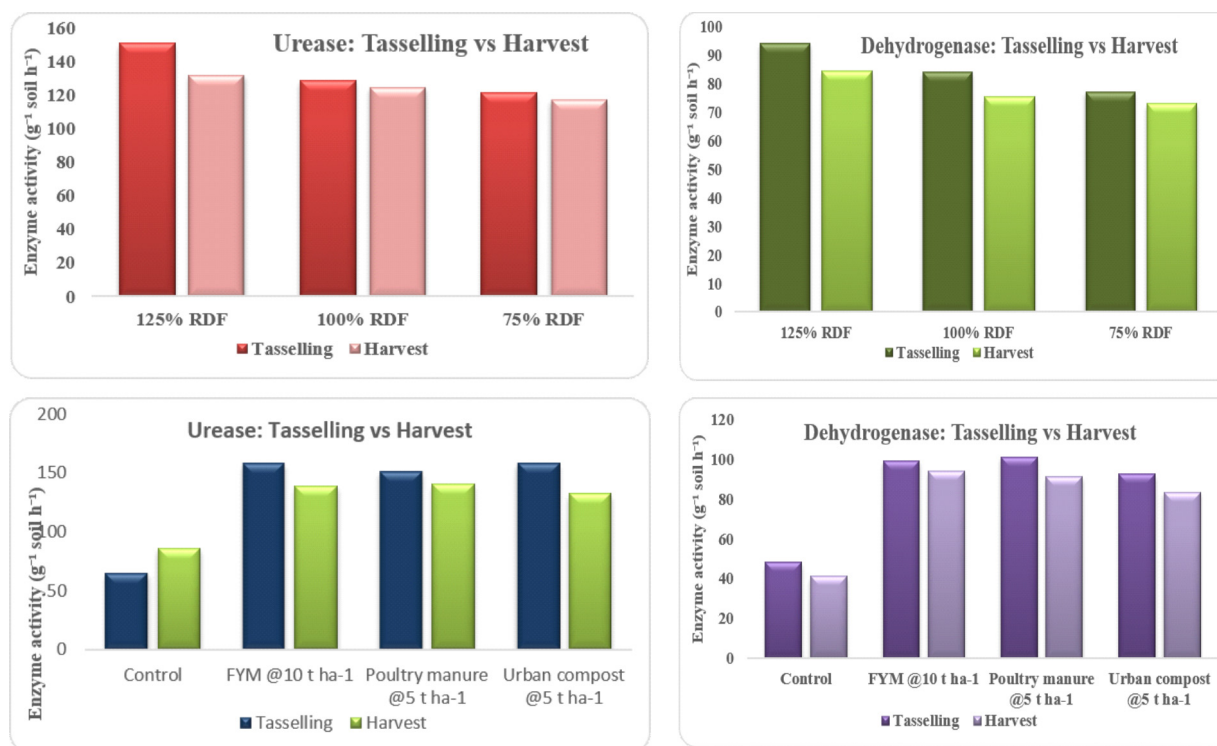


Fig. 1. Effect of INM practices on urease and dehydrogenase activity at tasseling and harvest stage maize crop

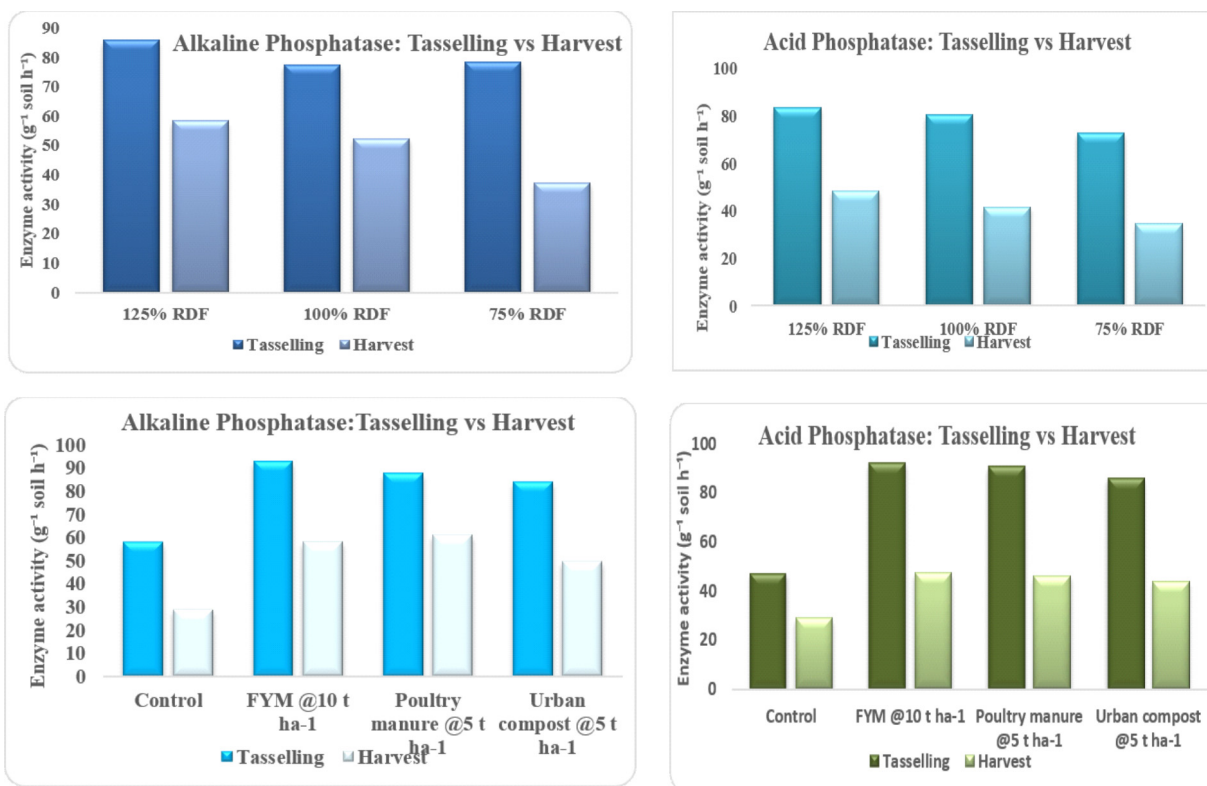


Fig. 2. Effect of INM practices on alkaline and acid phosphatase activity at tasseling and harvest stage maize crop

Among the organic nutrient sources, FYM @ 10 t ha⁻¹ consistently maintained higher enzyme activities than poultry manure and urban compost. Farmyard manure recorded the highest urease (158.68 µg NH₄⁺-N g⁻¹ h⁻¹), acid phosphatase (92.5 µg PNP g⁻¹ h⁻¹) and alkaline phosphatase (92.9 µg PNP g⁻¹ h⁻¹) activities at tasseling. The superior performance of FYM can be attributed to its gradual decomposition and continuous release of nutrients, which improve soil organic carbon status and provide a sustained energy source for soil microorganisms (Laxminarayana, 2023). Diacono and Montemurro, (2010) reported that regular application of FYM enhances soil aggregation, microbial habitat and nutrient availability, thereby stimulating enzyme synthesis. Poultry manure also recorded high enzyme activities, particularly dehydrogenase activity (101.2 µg TPF g⁻¹ h⁻¹), owing to its lower C:N ratio and rapid mineralization. Similar observations were reported by Yang *et al.*, (2023), who found that poultry manure accelerated microbial activity through the rapid release of available nutrients.

Higher urease activity under FYM and poultry manure treatments indicates enhanced nitrogen mineralization, while increased acid and alkaline

phosphatase activities reflect greater phosphorus transformation from organic to plant-available forms. Tabatabai and Bremner, (1972) highlighted the importance of urease in regulating soil nitrogen transformations, whereas phosphatase enzymes play a key role in phosphorus cycling. Similarly, dehydrogenase activity is considered a reliable indicator of overall microbial oxidative activity and soil biological functioning (Laxminarayana, 2023). Therefore, the enhanced enzyme activities observed under integrated nutrient management demonstrate improved nutrient cycling and soil fertility in maize.

Effect of Integrated Nutrient Management on Soil Enzyme Activities in Groundnut

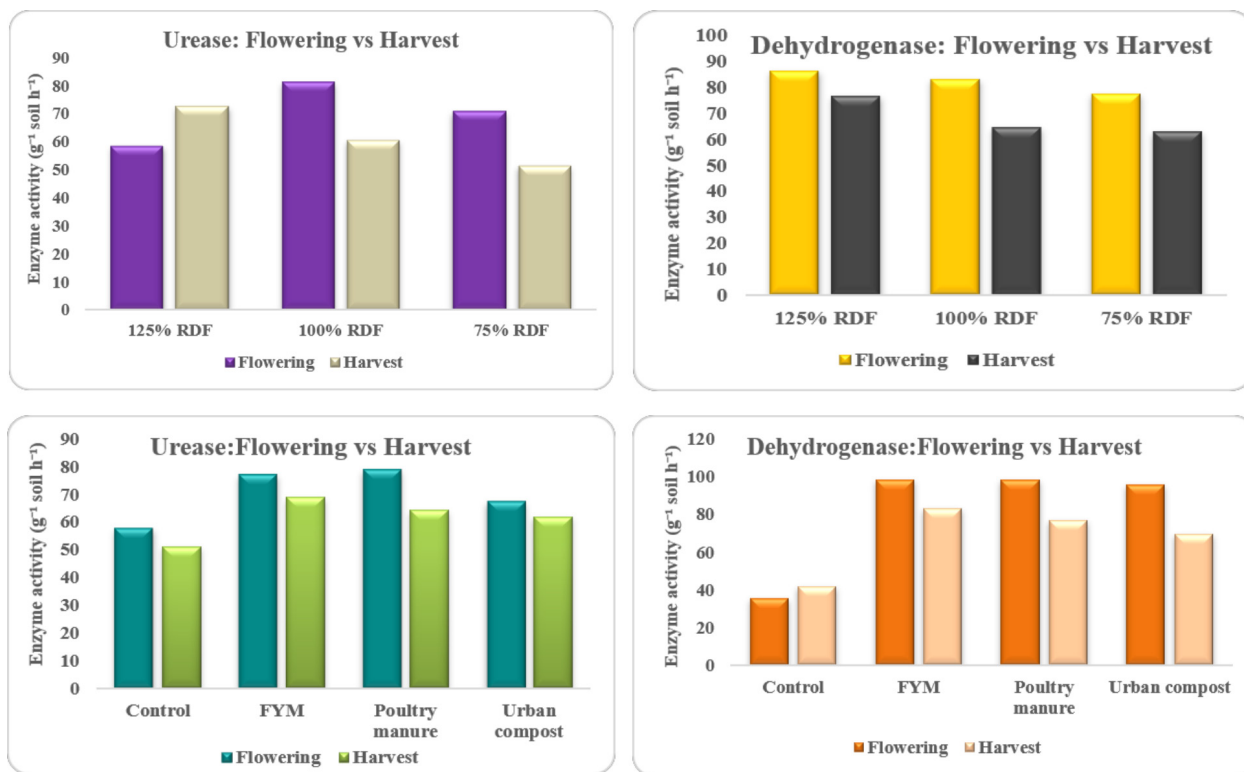
The response of soil enzymes to integrated nutrient management in groundnut followed trends similar to those observed in maize (Table 3 and 4; Fig. 3 and 4). Fertilizer levels significantly influenced enzymatic activities, with 125% RDF generally recording the highest values at harvest. Adequate nutrient availability under higher fertilizer levels likely supported greater root development and microbial activity, resulting in enhanced enzyme synthesis and nutrient transformations.

Table 3. Influence of integrated nutrient management on soil enzyme activities at the tasseling stage of groundnut crop

Treatments	Urease (µg NH ₄ ⁺ -N g ⁻¹ h ⁻¹)			Dehydrogenase (µg of TPF g ⁻¹ h ⁻¹)			Acid phosphatase (µg PNP g ⁻¹ h ⁻¹)			Alkaline phosphatase (µg PNP g ⁻¹ h ⁻¹)		
	2019	2020	pooled	2019	2020	pooled	2019	2020	pooled	2019	2020	pooled
Main plots												
M ₁ = 125 % RDF	57.4	59.6	58.5	84.3	88.4	86.4	72.0	70.5	71.2	74.0	77.5	80.8
M ₂ = 100 % RDF	80.3	82.1	81.2	80.9	85.0	83.0	69.3	72.8	71.1	75.3	77.2	76.3
M ₃ = 75 % RDF	69.8	71.8	70.8	75.6	79.7	77.7	64.8	67.7	66.3	65.6	67.5	66.6
SEm+	1.80	1.75	1.77	0.59	0.59	0.59	0.52	0.51	0.46	0.28	0.44	0.32
CD (P=0.05)	7.05	6.86	6.95	NS	NS	2.31	NS	NS	NS	1.09	1.72	1.25
Sub plots												
S ₁ = Control	56.5	58.7	57.6	33.6	37.7	35.7	42.6	47.4	45.0	49.6	50.9	50.3
S ₂ = FYM @ 10 tonnes ha ⁻¹	76.0	77.7	76.9	96.7	100.8	98.8	77.4	78.4	77.9	85.1	83.1	84.1
S ₃ = Poultry manure @ 5 tonnes ha ⁻¹	77.9	79.8	78.9	96.7	100.9	98.8	79.6	78.8	79.2	82.9	80.9	81.9
S ₄ = Urban compost @ 5 tonnes ha ⁻¹	66.3	68.5	67.4	94.0	98.2	96.1	75.2	76.9	76.0	82.4	81.5	81.9
SEm+	1.11	1.10	1.10	0.30	0.30	0.30	1.24	0.65	0.72	0.21	0.53	0.31
CD (P=0.05)	3.31	3.26	3.28	0.88	0.88	0.88	3.68	1.94	2.14	0.64	1.59	0.91
Interaction												
Sub at same level main (S × M)												
SEm+	3.34	3.29	3.31	0.89	0.89	0.89	3.71	1.96	2.16	0.64	1.60	0.92
CD (P=0.05)	NS	NS	NS	3.07	3.07	3.07	NS	NS	NS	2.22	NS	NS
Main at same or different level sub (M × S)												
SEm+	18.5	18.1	18.3	5.0	5.0	5.0	19.4	10.3	11.3	3.5	8.5	4.9
CD (P=0.05)	NS	NS	NS	18.3	18.3	18.3	NS	NS	NS	12.0	NS	NS

Table 4. Influence of integrated nutrient management on soil enzyme activities at the harvesting stage of groundnut crop

Treatments	Urease ($\mu\text{g NH}_4^+ \text{ N g}^{-1} \text{ h}^{-1}$)			Dehydrogenase ($\mu\text{g of TPF g}^{-1} \text{ h}^{-1}$)			Acid phosphatase ($\mu\text{g PNP g}^{-1} \text{ h}^{-1}$)			Alkaline phosphatase ($\mu\text{g PNP g}^{-1} \text{ h}^{-1}$)		
	2019	2020	pooled	2019	2020	pooled	2019	2020	pooled	2019	2020	pooled
Main plots												
M ₁ = 125 % RDF	59.9	85.3	72.6	76.4	77.3	76.9	67.6	63.6	65.6	57.6	57.2	57.4
M ₂ = 100 % RDF	55.5	65.4	60.4	64.1	65.0	64.5	65.0	63.5	64.2	50.7	52.7	51.7
M ₃ = 75 % RDF	47.3	55.5	51.4	62.6	63.4	63.0	60.5	58.4	59.4	40.7	46.9	43.8
SEm+	1.21	0.07	0.61	0.48	0.48	0.48	0.52	0.51	0.46	0.40	0.44	0.35
CD (P=0.05)	4.75	0.26	2.39	1.89	1.89	1.89	NS	NS	NS	1.59	1.72	1.38
Sub plots												
S ₁ = Control	48.1	54.0	51.0	41.6	42.4	42.0	38.3	38.1	38.2	34.6	41.6	38.1
S ₂ = FYM @ 10 tonnes ha ⁻¹	57.7	79.9	68.8	83.2	84.0	83.6	73.1	72.3	72.7	57.4	57.8	57.6
S ₃ = Poultry manure @ 5 tonnes ha ⁻¹	55.3	73.0	64.1	76.6	77.4	77.0	75.2	69.5	72.3	55.7	56.0	55.9
S ₄ = Urban compost @ 5 tonnes ha ⁻¹	55.8	68.1	61.9	69.5	70.3	69.9	70.9	67.5	69.2	51.0	53.6	52.3
SEm+	0.47	0.09	0.23	0.37	0.37	0.37	1.24	0.65	0.72	0.68	0.49	0.46
CD (P=0.05)	1.38	0.26	0.67	1.10	1.10	1.10	3.68	1.94	2.14	2.01	1.46	1.38
Interaction												
Sub at same level main (S × M)												
SEm+	1.40	0.26	0.68	1.11	1.11	1.11	3.71	1.96	2.16	2.03	1.47	1.39
CD (P=0.05)	4.84	0.92	2.36	3.84	3.84	3.84	NS	NS	NS	NS	NS	NS
Main at same or different level sub (M × S)												
SEm+	8.4	1.4	4.1	6.0	6.0	6.0	19.4	10.3	11.3	10.6	7.8	7.3
CD (P=0.05)	31.3	4.5	15.4	20.7	20.7	20.7	NS	NS	NS	NS	NS	NS

**Fig. 3.** Effect of INM practices on urease and dehydrogenase activity at flowering and harvest stage of groundnut crop

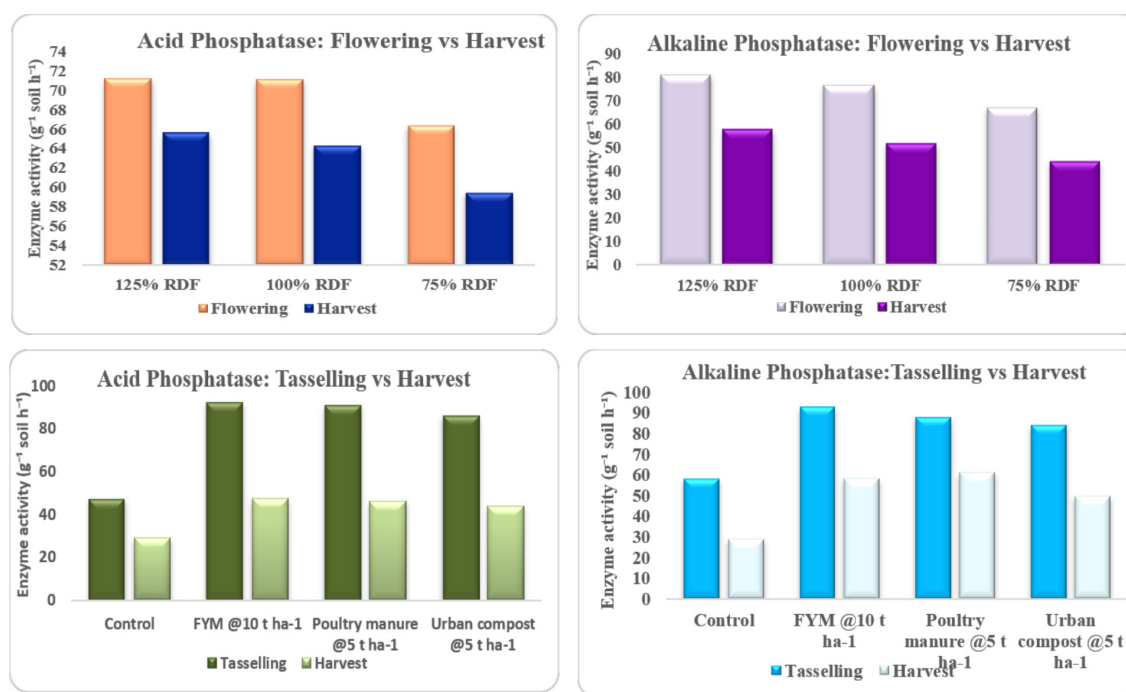


Fig. 4. Effect of INM practices on alkaline and acid phosphatase activity at flowering and harvest stage of ground crop

Enzyme activities were consistently higher at flowering than at harvest. During flowering, active root growth and increased rhizodeposition provide favorable conditions for microbial proliferation and enzyme production (Laxminarayana, 2023). As crop maturity approaches, reduced root activity and depletion of readily available substrates lead to lower enzymatic activity. Similar growth-stage-dependent variations in soil enzyme activity have been reported by Bana *et al.*, 2022, who observed higher biological activity during active crop growth compared to maturity stages.

Among the organic nutrient sources, FYM and poultry manure were markedly superior to urban compost and control treatments. Poultry manure recorded the highest urease ($78.9 \mu\text{g NH}_4^+-\text{N g}^{-1} \text{h}^{-1}$) and acid phosphatase ($79.2 \mu\text{g PNP g}^{-1} \text{h}^{-1}$) activities at flowering, whereas FYM recorded the highest dehydrogenase ($98.8 \mu\text{g TPF g}^{-1} \text{h}^{-1}$) and alkaline phosphatase ($84.1 \mu\text{g PNP g}^{-1} \text{h}^{-1}$) residual effect. Rayne and Aula, 2020 reported that FYM provides a continuous supply of organic substrates and nutrients through slow decomposition, thereby sustaining microbial activity over a longer period. In contrast, poultry manure releases nutrients rapidly and promotes immediate microbial responses, but its effect may diminish more quickly. At harvest, FYM enhanced phosphatase activities under FYM and poultry manure treatments indicate

improved phosphorus mineralization, which is particularly important in groundnut due to its relatively high phosphorus demand for root development, nodulation and pod formation (Bana *et al.*, 2024). Increased urease and dehydrogenase activities further suggest improved nitrogen transformation and microbial respiration. Similar beneficial effects of integrated nutrient management on soil enzyme activities have been documented by Bana *et al.* (2024), Krishna *et al.* (2025) and Ghasal *et al.* (2025).

Implications for Soil Health and Sustainable Nutrient Management

The present study demonstrates that integrated nutrient management enhances soil biological functioning by improving key enzymes involved in nitrogen and phosphorus cycling. Soil enzymes are widely regarded as sensitive indicators of soil health because they respond rapidly to changes in nutrient management and environmental conditions (Nannipieri *et al.*, 2017). The consistently higher enzyme activities observed under FYM and poultry manure treatments indicate improved nutrient transformation processes and greater biological activity within the soil ecosystem (Laxminarayana, 2023).

The superiority of FYM highlights the importance of maintaining soil organic matter for

sustaining microbial activity and enzyme production. As noted by Diacono and Montemurro, (2010), long-term application of organic manures improves soil structure, nutrient retention and biological functioning. The enhanced urease, dehydrogenase, acid phosphatase and alkaline phosphatase activities observed in the present study suggest improved nutrient-use efficiency and stronger nutrient cycling capacity under integrated nutrient management (Bana et al., 2022).

From a practical perspective, the combined application of FYM with recommended fertilizer doses can be considered a sustainable nutrient management strategy for maize-groundnut cropping systems (Laxminarayana, 2023). Such an approach not only supports crop productivity but also contributes to long-term soil health, resource conservation and resilience of agricultural systems under semi-arid conditions.

CONCLUSION

Integrated nutrient management significantly improved soil enzymatic activities in the maize-groundnut cropping system, indicating enhanced nutrient cycling and soil biological health. Among the fertilizer levels, 125% RDF generally recorded higher enzyme activities than 100% and 75% RDF. Among the organic nutrient sources, FYM @ 10 t ha⁻¹ consistently performed better than poultry manure and urban compost by sustaining higher urease, dehydrogenase, acid phosphatase, and alkaline phosphatase activities across crop growth stages.

Higher enzyme activities during tasseling in maize and flowering in groundnut highlighted the importance of active root growth and rhizosphere processes in regulating soil biological functions. The results demonstrate that integrating FYM with recommended fertilizer doses is an effective strategy for improving nutrient transformation, maintaining soil health, and supporting sustainable crop production in Alfisols.

From a practical perspective, the combined use of FYM and inorganic fertilizers can help farmers improve soil quality while maintaining crop productivity and reducing long-term dependence on chemical fertilizers. Future studies should focus on the long-term impacts of integrated nutrient management on soil carbon dynamics, nutrient-use efficiency, and climate-resilient agricultural production systems.

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