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Influence of zeolite and fertilizer dosages on macronutrient status of soil under incubation

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ABSTRACT

A laboratory incubation experiment was carried out at the College of Agriculture, Navile campus, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences (KSNUAHS), Shivamogga, to evaluate the influence of natural zeolite and graded fertilizer dosages on the release pattern of available nitrogen (N), phosphorus (P) and potassium (K) in an acidic sandy loam soil (Alfisol) of the Southern Transition Zone (Zone 7) of Karnataka. Processed soil (1 kg) was incubated at field capacity in a Completely Randomized Design with eleven treatments, comprising an absolute control, 75 and 100 per cent recommended dose of fertilizer (RDF, 25:50:25 kg N: P₂O₅:K₂O ha⁻¹) alone and in combination with zeolite at 50, 75, 100 and 150 kg ha⁻¹, replicated thrice. Soil samples drawn at 5, 10, 15, 30 and 60 days after incubation (DAI) were analyzed for available N, P and K. Available nitrogen and potassium did not differ significantly among treatments up to 10 DAI but diverged significantly from 15 DAI onward, with treatments receiving 100 kg ha⁻¹ zeolite (T₆) and 150 kg ha⁻¹ zeolite (T₇) along with 100 per cent RDF recording the highest values at 60 DAI (341.47 and 336.80 kg N ha⁻¹; 303.10 and 297.03 kg K ha⁻¹, respectively). Available phosphorus differed significantly from as early as 5 DAI, increased progressively up to 30 DAI in all nutrient-applied treatments (maximum 81.94 kg ha⁻¹ in T₇) and declined marginally thereafter, the decline being far smaller in zeolite-amended treatments than in RDF alone. All zeolite-amended treatments maintained available N, P and K above the initial soil status (323.80, 37.03 and 305.02 kg ha⁻¹, respectively) throughout the sixty-day incubation, whereas the absolute control declined continuously below the baseline. The results establish the slow and sustained nutrient-release behaviour of zeolite and identify 100 kg ha⁻¹ zeolite combined with 100 per cent RDF as the most effective combination for conserving soil macronutrient status.

Keywords: Zeolite, Incubation, Available nitrogen, Available phosphorus, Available potassium, Slow release, Alfisol

Introduction

Nutrient management is one of the most critical determinants of soil fertility and crop productivity in tropical agricultural systems. Continuous cultivation with imbalanced fertilizer use has led to progressive nutrient depletion, while applied nitrogen, phosphorus and potassium are subject to substantial losses through leaching, volatilization and fixation, particularly in coarse-textured, acidic soils (Baligar *et al.*, 1986) [1]. Fertilizer-use efficiency under tropical conditions is generally below 50 per cent for nitrogen, less than 10 per cent for phosphorus and around 40 per cent for potassium (Baligar *et al.*, 1986) [1] and about half of the world's agricultural soils are reported to be deficient in phosphorus (Lynch, 2011) [2].

Zeolites are naturally occurring crystalline hydrated aluminosilicate minerals of alkali and alkaline-earth metals, built up of a three-dimensional framework of AlO₄ and SiO₄ tetrahedra that generates a system of channels, cavities and pores of molecular dimensions (Ming *et al.*, 1989; Ramesh *et al.*, 2014) [3, 4]. Isomorphous substitution of aluminium for silicon in the framework imparts a permanent negative charge with a marked preference for monovalent cations, conferring on zeolites a very high cation exchange capacity (CEC), high water-holding capacity in the free channels and high adsorption capacity (Vaughan, 1978; Mumpton, 1999) [6, 5]. These properties enable zeolites to function as carriers and controlled-release dispensers of plant nutrients, thereby improving nutrient-use efficiency and soil fertility (Sangeetha *et al.*, 2016; Jakkula *et al.*, 2018) [8, 7].

The agronomic relevance of these mechanisms is amplified in Alfisols, the soil order to which the sandy loam of the present study belongs, since their inherently low native cation exchange capacity and pronounced susceptibility to nutrient leaching under intense tropical rainfall make them especially reliant on amendments capable of expanding the exchange complex. Working specifically in semi-arid Alfisols, Ramesh *et al.* (2024b) [9] demonstrated that locally sourced mordenite zeolite, characterized by a cation exchange capacity several-fold higher than that of the unamended soil, markedly improved the water- and nutrient-use efficiency of NH₄⁺, phosphorus and potassium when combined with recommended fertilization,

attributing the response to the combined action of high specific surface area, internal void structure and moisture-retentive porosity of the mineral. The selectivity of the zeolite framework for particular cations is not uniform but follows a defined exchange series governed by ionic radius, hydration energy and charge density, so that monovalent ions of intermediate hydrated radius such as NH_4^+ and K^+ are held preferentially over more strongly hydrated or more weakly charged species (Wang *et al.*, 2010) [10]. This selective, reversible exchange behaviour, rather than irreversible fixation, is what permits zeolite to function simultaneously as a nutrient reservoir and a slow-release dispenser, distinguishing its mode of action from that of conventional soil conditioners such as farmyard manure or lime.

Laboratory incubation studies provide a controlled means of characterizing the nutrient-release behaviour of soil amendments independent of the confounding influences of weather, irrigation and crop uptake that operate under field conditions. Zeolite has been reported to significantly enhance available N, P and K over a 90-days incubation in tropical Ultisols (Ramesh *et al.*, 2024a) [11], to reduce ammonia volatilization and improve retention of exchangeable ammonium in sandy loam soil (Rabai *et al.*, 2012) [12], to raise soil pH and favours moderately labile, slow-release phosphorus fractions in acid soils when combined with phosphatic fertilizers (Hasbullah *et al.*, 2020) [13] and to increase the adsorption of NH_4^+ and K^+ while lowering their desorption, in addition to improving soil pH buffering capacity (Palanivell *et al.*, 2021) [14]. However, information on the combined influence of graded zeolite rates with varying fertilizer dosages on the release pattern of all three major nutrients in the acid sandy loam soils typical of the Southern Transition Zone of Karnataka is limited.

The present investigation was therefore undertaken with the objective of studying the influence of zeolite and fertilizer dosages on the macronutrient (nitrogen, phosphorus and potassium) status of soil under incubation, so as to identify the rate of zeolite application that most effectively conserves and sustains nutrient availability prior to its evaluation under field conditions.

Material and methods

Experimental site

The incubation study was conducted at the College of Agriculture, Navale campus, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences (KSNUAHS), Shivamogga (13° 58' to 14° 1' N latitude and 75° 34' to 75° 42' E longitude; altitude 650 m above mean sea level), which falls under the Southern Transition Zone (Zone 7) of Karnataka, during 2026.

Experimental design and treatments

The incubation study was laid out in a Completely Randomized Design (CRD) with eleven treatments replicated thrice, using 1 kg of processed soil per treatment maintained at field capacity moisture throughout the incubation period. The treatments imposed, on the basis of the recommended dose of fertilizer (RDF: 25:50:25 kg N:P₂O₅:K₂O ha⁻¹) applied through urea, single super phosphate and muriate of potash, were as follows: T₁ - Absolute control; T₂ - 100% RDF; T₃ - 75% RDF; T₄ - 100% RDF + zeolite @ 50 kg ha⁻¹; T₅ - 100% RDF + zeolite @ 75 kg ha⁻¹; T₆ - 100% RDF + zeolite @ 100 kg ha⁻¹; T₇ - 100% RDF + zeolite @ 150 kg ha⁻¹; T₈ - 75% RDF + zeolite @ 50 kg ha⁻¹; T₉ - 75% RDF + zeolite @ 75 kg ha⁻¹; T₁₀ - 75% RDF + zeolite @ 100 kg ha⁻¹; T₁₁ - 75% RDF + zeolite @ 150 kg ha⁻¹.

Initial soil and zeolite characterization

Bulk surface soil was collected from the Southern Transitional Zone of Karnataka (Agro-Climatic Zone VII), air-dried under shade, powdered and sieved through a 2 mm mesh. The processed soil was sandy loam in texture with an acidic reaction (pH 5.80), electrical conductivity of 0.31 dS m⁻¹ and organic carbon content of 4.02 g kg⁻¹. The initial available N, P₂O₅ and K₂O status of the soil was 323.80, 37.03

and 305.02 kg ha⁻¹, respectively and the cation exchange capacity was 15.20 cmol (p⁺) kg⁻¹ (Table 1).

The zeolite used was procured from Global Earths Chemicals, Vijayapura, Karnataka. Characterization was performed after acid digestion (HNO₃-HClO₄, supplemented with HF for silicon estimation), which revealed an alkaline reaction (pH 7.68), electrical conductivity of 0.08 dS m⁻¹, organic carbon of 4.84 g kg⁻¹, a very high cation exchange capacity of 120 cmol (p⁺) kg⁻¹ and Ca, Mg, Al₂O₃ and SiO₂ contents of 5.20, 1.20, 13.00 and 60.00 per cent, respectively (Table 2).

Table 1. Initial physico-chemical properties of the experimental soil

Property	Value
pH (1:2.5)	5.80
Electrical conductivity (dS m ⁻¹)	0.31
Organic carbon (g kg ⁻¹)	4.02
Textural class	Sandy loam
Available N (kg ha ⁻¹)	323.80
Available P ₂ O ₅ (kg ha ⁻¹)	37.03
Available K ₂ O (kg ha ⁻¹)	305.02
Available S (mg kg ⁻¹)	18.01
Exchangeable Ca [cmol (p ⁺) kg ⁻¹]	4.75
Exchangeable Mg [cmol (p ⁺) kg ⁻¹]	2.50
Cation exchange capacity [cmol (p ⁺) kg ⁻¹]	15.20

Table 2. Characterization of zeolite used in the study

Parameter	Value
pH	7.68
Electrical conductivity (dS m ⁻¹)	0.08
Organic carbon (g kg ⁻¹)	4.84
Cation exchange capacity [cmol (p ⁺) kg ⁻¹]	120.00
Ca (%)	5.20
Mg (%)	1.20
Al ₂ O ₃ (%)	13.00
SiO ₂ (%)	60.00

Results and discussion

Available nitrogen status of soil under incubation

Available nitrogen did not differ significantly among treatments at 5 and 10 DAI. At 5 DAI, the numerically highest available N (347.70 kg ha⁻¹) was recorded in T₇ (100% RDF + 150 kg ha⁻¹ zeolite) and the lowest (322.27 kg ha⁻¹) in T₁. At 10 DAI, the numerically highest value (359.20 kg ha⁻¹) was recorded in T₂ (100% RDF) and the lowest (329.53 kg ha⁻¹) in T₈. From 15 DAI onward, treatment differences became significant. At 15 DAI, T₇ recorded the highest available N (355.63 kg ha⁻¹), on par with T₆ (354.97 kg ha⁻¹) and T₁₀ (352.10 kg ha⁻¹); the lowest (314.93 kg ha⁻¹) was recorded in T₁. At 30 DAI, T₇ remained highest (346.67 kg ha⁻¹), on par with T₆ (342.37 kg ha⁻¹) and T₁₁ (342.23 kg ha⁻¹), while T₁ recorded the lowest (314.57 kg ha⁻¹). At 60 DAI, T₆ recorded the highest available N (341.47 kg ha⁻¹), on par with T₇ (336.80 kg ha⁻¹) and T₁₁ (336.23 kg ha⁻¹), whereas T₁ remained lowest (313.30 kg ha⁻¹). Notably, every zeolite-amended treatment maintained available N above the initial soil status (323.80 kg ha⁻¹) throughout the 60-day incubation, while T₁ remained below this baseline at every interval (Table 3).

Table 3. Available nitrogen (kg ha^{-1}) in soil under incubation as influenced by zeolite and fertilizer dosages

Treatments	Available nitrogen N (kg ha^{-1})				
	5 DAI	10 DAI	15 DAI	30 DAI	60 DAI
T ₁ : Absolute control	322.27	329.77	314.93	314.57	313.30
T ₂ : 100 % RDF	342.63	341.33	334.10	336.53	330.13
T ₃ : 75 % RDF	335.97	336.73	324.10	320.70	318.73
T ₄ : 100 % RDF + 50 kg ha^{-1} zeolite	347.63	355.00	342.50	339.13	330.13
T ₅ : 100 % RDF + 75 kg ha^{-1} zeolite	342.47	354.20	351.93	341.03	334.70
T ₆ : 100 % RDF + 100 kg ha^{-1} zeolite	347.63	358.70	354.97	342.37	341.47
T ₇ : 100 % RDF + 150 kg ha^{-1} zeolite	347.70	359.20	355.63	346.67	336.80
T ₈ : 75 % RDF + 50 kg ha^{-1} zeolite	332.60	329.53	336.17	335.97	324.00
T ₉ : 75 % RDF + 75 kg ha^{-1} zeolite	334.90	336.73	340.53	330.83	329.77
T ₁₀ : 75 % RDF + 100 kg ha^{-1} zeolite	338.03	330.37	352.10	338.47	332.27
T ₁₁ : 75 % RDF + 150 kg ha^{-1} zeolite	347.23	355.60	352.03	342.23	336.23
S. Em $\pm$	10.21	11.55	8.98	5.83	6.08
C.D. @ 5%	NS	NS	26.49	17.20	17.95

The failure of treatments to differ significantly in available nitrogen up to 10 DAI, followed by significant divergence from 15 DAI onward, is itself the most instructive feature of the incubation study and constitutes direct evidence of slow-release behaviour. In the first ten days, the mineral nitrogen released from urea hydrolysis was comparable across all fertilized treatments; as time advanced, the unamended treatments lost nitrogen through volatilization and nitrification-driven mobility, whereas the zeolite-amended treatments retained it. The mechanism underlying this retention is the selective adsorption of ammonium ions within the tetrahedral aluminosilicate framework of the mineral. Zeolites are crystalline hydrated aluminosilicates whose three-dimensional network of channels, cavities and pores accommodates exchangeable cations (Ming *et al.*, 1989) [3] and the isomorphous substitution of aluminium for silicon generates a permanent negative charge with a marked preference for monovalent cations such as NH_4^+ and K^+ (Vaughan, 1978) [6]. Ammonium adsorption by clinoptilolite increases with soil pH in the range 4 to 7 and with the initial ammonium concentration of the medium (Kithome *et al.*, 1999) [15]. Clinoptilolite added to a sandy loam soil has been reported to reduce ammonia loss appreciably by favouring retention of ammonium over its conversion to ammonia gas, so that zeolite-amended soils held higher available nitrogen at the end of incubation than urea applied alone (Rabai *et al.*, 2012) [12], a finding closely mirrored by the present results. Amendment of light-textured soils with clinoptilolite has likewise been shown to curtail nitrogen losses through both ammonia volatilization and nitrate leaching by enhancing ammonium retention and microbial immobilization (He *et al.*, 1999) [16] and a 90-day incubation in tropical acid soils demonstrated that zeolite significantly increased available N, P and K, offering a route to reduced dependence on chemical fertilizers (Ramesh *et al.*, 2024a) [11].

A point of considerable practical relevance emerges on comparing the incubation values with the initial available nitrogen status of the soil

(323.80 kg ha^{-1}). T₃ (75% RDF), which received a reduced fertilizer dose without any amendment, held only 318.73 kg ha^{-1} at 60 DAI, whereas T₁₁ (75% RDF + 150 kg ha^{-1} zeolite) at the identical reduced fertilizer dose held 336.23 kg ha^{-1} , statistically on par with the best treatment. This demonstrates that the amendment compensated, in terms of retained nitrogen, for a twenty-five per cent reduction in fertilizer dose, consistent with the finding that zeolite addition along with half the recommended nitrogen and potassium reduced fertilizer cost without compromising crop performance (Zhaohui *et al.*, 2013) [17].

Available phosphorus status of soil under incubation

Unlike nitrogen, available phosphorus differed significantly among treatments from 5 DAI itself and at every subsequent interval (Table 4). At 5 DAI, T₆ (100% RDF + 100 kg ha^{-1} zeolite) recorded the highest available P (57.83 kg ha^{-1}), on par with T₇ (57.27 kg ha^{-1}) and T₅ (56.12 kg ha^{-1}); the lowest (36.39 kg ha^{-1}) was recorded in T₁. At 10 DAI, T₆ remained highest (64.70 kg ha^{-1}), on par with T₇ (64.65 kg ha^{-1}) and T₄ (64.47 kg ha^{-1}); T₁ recorded the lowest (34.33 kg ha^{-1}). At 15 DAI, T₆ recorded 73.28 kg ha^{-1} , on par with T₇ (71.15 kg ha^{-1}); T₁ recorded the lowest (34.05 kg ha^{-1}). Available phosphorus rose progressively up to 30 DAI in all nutrient-applied treatments, the highest value (81.94 kg ha^{-1}) being recorded in T₇, on par with T₆ (81.60 kg ha^{-1}) and T₁₁ (78.18 kg ha^{-1}); the lowest (32.57 kg ha^{-1}) remained in T₁. Thereafter, available P declined marginally by 60 DAI in all treatments, with T₆ recording the highest value (77.35 kg ha^{-1}), on par with T₇ (77.33 kg ha^{-1}) and T₁₁ (74.83 kg ha^{-1}), while T₁ continued to decline to its lowest value (31.52 kg ha^{-1}). In contrast to the nutrient-applied treatments, T₁ showed a continuous decline throughout the incubation period, from 36.39 kg ha^{-1} at 5 DAI to 31.52 kg ha^{-1} at 60 DAI.

Table 4. Available phosphorus (kg ha^{-1}) in soil under incubation as influenced by zeolite and fertilizer dosages

Treatments	Available phosphorus P_2O_5 (kg ha^{-1})				
	5 DAI	10 DAI	15 DAI	30 DAI	60 DAI
T ₁ : Absolute control	36.39	34.33	34.05	32.57	31.52
T ₂ : 100 % RDF	54.80	61.87	61.00	69.90	62.12
T ₃ : 75 % RDF	50.41	55.69	53.38	59.48	53.87
T ₄ : 100 % RDF + 50 kg ha^{-1} zeolite	55.89	64.47	65.37	71.66	67.49
T ₅ : 100 % RDF + 75 kg ha^{-1} zeolite	56.12	64.34	67.04	74.68	71.37
T ₆ : 100 % RDF + 100 kg ha^{-1} zeolite	57.83	64.70	73.28	81.60	77.35
T ₇ : 100 % RDF + 150 kg ha^{-1} zeolite	57.27	64.65	71.15	81.94	77.33
T ₈ : 75 % RDF + 50 kg ha^{-1} zeolite	49.90	55.09	58.01	65.06	61.46

(continued on next page)

Treatments	Available phosphorus P ₂ O ₅ (kg ha ⁻¹)				
	5 DAI	10 DAI	15 DAI	30 DAI	60 DAI
T ₉ : 75 % RDF + 75 kg ha ⁻¹ zeolite	50.82	56.12	60.47	68.18	65.46
T ₁₀ : 75 % RDF + 100 kg ha ⁻¹ zeolite	52.18	58.82	66.49	74.97	71.46
T ₁₁ : 75 % RDF + 150 kg ha ⁻¹ zeolite	53.72	57.18	67.58	78.18	74.83
S. Em ±	1.24	1.57	1.53	1.34	1.44
C.D. @ 5%	3.65	4.62	4.50	3.95	4.24

Available phosphorus rose progressively up to 30 DAI in all nutrient-applied treatments and declined thereafter, reflecting the dissolution of applied single super phosphate together with mineralization processes up to 30 DAI, followed by the onset of fixation by iron and aluminium oxides characteristic of acid soils. The important observation is that the extent of this decline was much smaller in zeolite-amended treatments; between 30 and 60 DAI, T₆ lost only 4.25 kg ha⁻¹ of available phosphorus, whereas T₂ (100% RDF, without amendment) lost 7.78 kg ha⁻¹. Three mechanisms explain this protective effect. First, clinoptilolite amendment of acid soils raises soil reaction and lowers exchangeable aluminium and titratable acidity and although immediate phosphorus availability is not always altered, zeolite favours accumulation of moderately labile aluminium-, iron- and calcium-bound phosphorus fractions that behave as slow-release reserves rather than irreversibly fixed forms (Hasbullah *et al.*, 2020) [13]. Second, the exchange-induced dissolution mechanism operating in zeolite-phosphate systems releases phosphorus gradually in response to plant demand rather than in a single flush (Handreck, 1997) [18] and clinoptilolite has been shown to lower the initial rate of phosphorus release while raising the average rate of dissolution over the whole period (He *et al.*, 1999) [16]. Third, ammonium- and potassium-saturated clinoptilolite increases phosphorus solubility while si-

multaneously supplying NH₄⁺ and K⁺ to the soil solution, so that the amendment performs a dual nutritional function (Hua *et al.*, 2006) [19]. The magnitude of the response observed here, with available phosphorus in T₆ at 60 DAI being nearly two and a half times that in T₁, is consistent with the general finding that zeolites raise phosphorus availability from phosphatic sources through their ion-exchange properties (Jakkula *et al.*, 2018) [7].

Available potassium status of soil under incubation

Available potassium followed a pattern similar to that of available nitrogen, with treatments remaining statistically at par at 5 and 10 DAI and differing significantly from 15 DAI onward (Table 5). At 5 DAI, the numerically highest available K (324.43 kg ha⁻¹) was recorded in T₇ and the lowest (301.83 kg ha⁻¹) in T₈. At 10 DAI, the highest value (327.40 kg ha⁻¹) was recorded in T₅ and the lowest (305.63 kg ha⁻¹) in T₉. At 15 DAI, T₇ recorded the highest available K (317.20 kg ha⁻¹), on par with T₆ (315.50 kg ha⁻¹) and T₁₁ (313.47 kg ha⁻¹); the lowest (287.47 kg ha⁻¹) was recorded in T₁. At 30 DAI, T₆ recorded the highest value (310.50 kg ha⁻¹), on par with T₇ (308.23 kg ha⁻¹) and T₁₁ (307.30 kg ha⁻¹); T₁ recorded the lowest (284.73 kg ha⁻¹). At 60 DAI, T₆ recorded the highest available K (303.10 kg ha⁻¹), on par with T₇ (297.03 kg ha⁻¹) and T₅ (296.97 kg ha⁻¹); T₁ remained the lowest (276.93 kg ha⁻¹).

Table 5. Available potassium (kg ha⁻¹) in soil under incubation as influenced by zeolite and fertilizer dosages

Treatments	Available potassium K ₂ O (kg ha ⁻¹)				
	5 DAI	10 DAI	15 DAI	30 DAI	60 DAI
T ₁ : Absolute control	306.83	306.23	287.47	284.73	276.93
T ₂ : 100 % RDF	323.53	315.10	294.87	296.20	287.43
T ₃ : 75 % RDF	303.37	308.80	297.20	291.83	282.57
T ₄ : 100 % RDF + 50 kg ha ⁻¹ zeolite	321.93	318.10	303.37	305.17	293.37
T ₅ : 100 % RDF + 75 kg ha ⁻¹ zeolite	308.03	327.40	308.73	306.30	296.97
T ₆ : 100 % RDF + 100 kg ha ⁻¹ zeolite	322.43	317.70	315.50	310.50	303.10
T ₇ : 100 % RDF + 150 kg ha ⁻¹ zeolite	324.43	323.37	317.20	308.23	297.03
T ₈ : 75 % RDF + 50 kg ha ⁻¹ zeolite	301.83	315.77	293.13	301.73	281.77
T ₉ : 75 % RDF + 75 kg ha ⁻¹ zeolite	305.07	305.63	296.47	298.37	286.43
T ₁₀ : 75 % RDF + 100 kg ha ⁻¹ zeolite	309.93	313.63	305.47	307.20	295.43
T ₁₁ : 75 % RDF + 150 kg ha ⁻¹ zeolite	320.87	315.73	313.47	307.30	296.67
S. Em ±	7.67	9.32	6.09	5.68	5.67
C.D. @ 5%	NS	NS	17.98	16.76	16.73

Taken together, the incubation results show that all zeolite-amended treatments maintained available N, P and K above the initial soil status throughout the 60-day period, whereas the absolute control (T₁) declined continuously below the baseline for all three nutrients, confirming the nutrient conserving effect of zeolite in this acid sandy loam soil.

Available potassium behaved much like available nitrogen, treatments remaining statistically indistinguishable at 5 and 10 DAI and differing significantly from 15 DAI onward. Potassium is lost from light-textured soils primarily through leaching and through fixation in the interlayer positions of clay minerals, its use efficiency being restricted to about 40 to 70 per cent of the applied quantity (Baligar *et al.*, 1986) [1]. The strong preference of the zeolite framework for monovalent cations (Vaughan, 1978) [6] means that K⁺ released from muriate of potash is held on the exchange complex of the amendment instead of

moving down the profile. Direct evidence for this comes from sorption-desorption studies in acid soils amended with graded rates of clinoptilolite, in which zeolite markedly increased adsorption of both NH₄⁺ and K⁺ and, importantly, coupled higher potassium adsorption with lower potassium desorption, indicating that the mineral locks up the element against leaching while retaining it as a plant-accessible reservoir; the same study also reported improved pH buffering capacity, critical to macronutrient availability in weathered acid soils (Palaniyell *et al.*, 2021) [14]. Enhancement of available soil potassium and its subsequent uptake following zeolite application has also been documented (Kavoosi, 2007) [20], as has an increase in the concentration of calcium, sodium and potassium in zeolite-treated soils (Ghazavi, 2015) [21]. The three properties of zeolite of greatest agricultural interest, namely high cation exchange capacity, high water-holding capacity in the free channels and high adsorption capacity

(Mumpton, 1999) [5], thus operated together in this incubation study to conserve all three major nutrients. These sorption-desorption patterns are consistent with controlled kinetic studies on clinoptilolite, which show that potassium desorption from zeolite-amended systems proceeds in two distinct phases, an initial rapid release lasting less than 200 hours followed by a much slower phase extending to several weeks, with the desorption rate accelerating in proportion to the calcium and ammonium concentration of the surrounding solution because these divalent and monovalent competitors progressively displace K^+ from exchange sites (Rezaei *et al.*, 2009) [22]. Field-scale confirmation of this behaviour comes from a two-year trial in which incorporation of zeolite together with graded potassium fertilizer increased the cumulative potassium release rate constant by over 13 per cent relative to the unamended control, the effect being attributed to the mineral's capacity to intercept K^+ before it could be fixed in the interlayer positions of clay minerals or lost to leaching (Karim *et al.*, 2022) [23]. The two-phase release pattern reported in these kinetic studies mirrors the trajectory observed in the present investigation, wherein available potassium in zeolite-amended treatments rose sharply during the first fortnight and thereafter declined only gradually, in contrast to the more precipitous decline recorded in treatments receiving fertilizer without the amendment.

Conclusion

The incubation study clearly demonstrated the slow and sustained nutrient-release behaviour of natural zeolite when combined with recommended fertilizer dosages in an acidic sandy loam soil. Available nitrogen and potassium did not differ significantly among treatments up to 10 DAI but diverged significantly from 15 DAI onward, while available phosphorus differed significantly from as early as 5 DAI and peaked at 30 DAI before declining marginally, with the decline being appreciably smaller in zeolite-amended soils. Treatments receiving 100 per cent RDF combined with 100 or 150 kg ha⁻¹ zeolite (T₆ and T₇) consistently recorded the highest and statistically comparable levels of available N, P and K throughout incubation, while treatment T₁₁ (75% RDF + 150 kg ha⁻¹ zeolite) demonstrated that a twenty-five per cent reduction in fertilizer dose could be compensated by zeolite application. All zeolite-amended treatments closed the incubation period with available N, P and K above the initial soil status, whereas the absolute control declined continuously below baseline. It may therefore be concluded that the application of 100 kg ha⁻¹ zeolite along with the recommended dose of fertilizer is the most effective combination for conserving and sustaining the macronutrient status of acid sandy loam soils under incubation, providing a sound basis for its evaluation under field conditions.

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