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RESEARCH ARTICLE

Soil pH, salinity and nutrient release dynamics in paddy soil influenced by varied levels of NPK fertilizers: Anaerobic incubation study

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Abstract

An anaerobic incubation study was conducted in paddy soil with varying levels of NPK fertilizers. Under submerged conditions, the pH of the soil was greatly influenced by the addition of nitrogen (N) at two different levels: 125 % and 150 % N + recommended phosphorus and potassium (Rec PK). Soil treated with 150 % N + Rec PK resulted in a lower soil pH than other treatments, as evidenced by the notable decrease in soil pH to 6.23 at 14 days after incubation (DAI). When compared to other treatments, 150 % P + Rec NK released more soluble salts at 28 DAI and the highest soil EC value measured was 1.39 dS m^{-1}. With respect to macronutrient availability, the maximum N availability was observed in the 150 % N + Rec PK 28 DAI (236 kg ha^{-1}), while the highest available P was found to be (37.55 mg kg^{-1}) noticed in the 150 % P + Rec NK treatment. The highest available K content was recorded to be 243 kg ha^{-1} and 234 kg ha^{-1} in soil treated with 150 % K and 125 % K respectively at 28 DAI. Under anaerobic conditions, a higher release of available NPK was observed between 21 and 28 DAI. Higher nutrient release throughout the incubation period was observed when the NPK level increased to 150%. Increasing the level of NPK to 150 % revealed higher nutrient release during the period of incubation under submerged conditions which can be beneficial for plant grown under nutrient deficit condition.

Keywords

macronutrients; paddy soil; salinity; soil reaction; submerged soil

Introduction

Nutrient availability and the richness of surface soil are the primary determinants of agricultural farming activities (1). The nutrient supply is mostly determined by soil fertility, which is also currently controlled by humans. The soil was once fertile, but shifting cultivation was replaced by intense cropping, which reduced the soil's productivity. As crop development has increased, the demand for nutrients in the soil has increased, with high-yielding crop varieties responding positively to the application of inorganic fertilizers (2).

Fertilizers are inorganic materials that are added to soil to provide essential nutrients that may be deficient in the soil naturally. It is primarily used to improve crop growth and supplement the soil with nutrients. Although fertilizer application may initially boost output, it also contributes to the depletion of native soil nutrient reserves. The addition of inorganic fertilizers has attempted to address the nutritional imbalance between crop uptake and replenishment. As a result, a significant portion of the productivity gains can be ascribed to the increased production and application of fertilizer.

However, many farmers are only aware of the role of macronutrients: nitrogen, phosphorus and potassium in soil fertility, while secondary and micronutrients are often overlooked (3). According to estimates, 40 % of soils have a S deficiency and 49 % have at least one micronutrient deficiencies (33 % for B, 12 % for Fe and less than 5 % for Cu and Mn). This kind of nitrogen scarcity decreased the effectiveness of NPK fertilizers.

Balanced fertilization refers to the application of an appropriate dosage and ratio of fertilizer based on the nutrient requirements of crops, the soil's nutrient supplying capacity, and the need to maintain nutrient balance between the applied fertilizer and the soil's natural composition. For example, a recent study showed that N, P and K fertilizers have different effects on both crop yield and quality (4). Studies indicate that moderate application of nitrogen, phosphate and potassium effectively enhances soil and leaf nutrient content, enhancing crop yield and quality (5).

However, excessive fertilizer application can cause severe soil nutrient imbalance, which induces leaf nutrient imbalance, ultimately affecting crop yield and economic efficiency. In actual agricultural practices, the proportions of N, P and K are often misbalanced due to the lack of scientifically determined ratios, negatively impacting nutrient absorption and utilization by plants. This imbalance leads to reduced crop yield and quality while also increasing the risk of nutrient loss and environmental pollution. Therefore, maintaining an optimal N, P and K ratio can significantly enhance plant growth while reducing the overall fertilizer requirement (6).

Furthermore, overuse of fertilizers will acidify the soil, resulting in a serious nutrient imbalance that will impact yield and economic efficiency by causing leaf nutrient deficiencies (7). The lack of scientific nutrient management results in frequent discrepancies in N, P and K levels, affecting nutrient uptake efficiency, lowering yield and quality and contributing to nutrient runoff and environmental contamination. Consequently, adopting a well-balanced N, P and K fertilization strategy can significantly promote plant growth, enhance soil fertility and reduce excessive fertilizer application (8).

Rice (*Oryza sativa* L.) is the staple food for most of the population in the world. At present, rice cultivation spans approximately 158 million ha throughout the world. China and India account for 55 % of world rice production (9). In south India, rice is the major food grain, which is cultivated under wet conditions. In Coimbatore district, rice is cultivated under larger area of about 2000 ha respectively.

As rice is a heavy feeder of nutrients, excessive dumping of nutrients into the soil causes stagnant and decline in yield. Further, the farmers often apply a higher quantity of fertilizers to get maximum yield; however, this practice contributes to a decline in nutrient use efficiency in rice ecosystems due to nutrient losses-particularly nitrogen (N)-through runoff, volatilization and leaching (10).

Laboratory- based soil incubation studies are helpful to analyze the mineralization process of both native and applied nutrients in soil. The quantity and rate of nutrient release from applied fertilizers play a critical role in determining crop performance at various growth stages of rice crop under anaerobic conditions. Furthermore, the impact of imbalanced NPK fertilizers application on soil quality and yield decline necessitates detailed investigation.

In this study, varied level of inorganic fertilizers was examined to assess their pattern of nutrient release in soil under anaerobic conditions. This evaluation aims to substantiate the effects of excessive fertilizer application on soil nutrient availability, which can inform recommendations for optimal fertilization strategies to enhance rice growth and productivity in field conditions. Thus, this experiment was undertaken to study the effects of excessive inorganic fertilizers use on nutrient release dynamics in anaerobic soils.

Materials and Methods

Collection of bulk soil samples

The soil used in this study was collected from the upper layer of surface horizon (0-15 cm) of a rice-growing farmer's field in Avarangattuvayal, Thondamuthur Block, Coimbatore District, to study the nutrient release pattern in response to different levels of NPK fertilizers application under submerged conditions. The soil used in the experiment was classified as Typic Haplustert with a clay loam texture.

For the experiment, polythene containers, each carrying 100 g of processed soil, were arranged in a completely randomized design with three replications. The required quantity of water was added based on the field capacity (41.2 %, w/w) to maintain submerged condition throughout the two-month incubation period. The containers were kept open at room temperature and soil moisture levels were monitored every three days by weighing the containers. Submerged conditions were maintained by the periodic addition of distilled water as needed.

Treatment details

The general fertilizer recommendation as given in crop production guide of Tamil Nadu Agricultural University (TNAU) was followed for this study. The recommended fertilizer rate for rice was 150:50:50 kg ha^{-1} of N: P_2O_5:K_2O. Straight fertilizers viz., urea, diammonium phosphate and muriate of potash, were used as the source of NPK respectively.

The fertilizer treatments comprised of:

T1-100 % RDF

T2-125% Rec N + 100% Rec PK

T3-150% Rec N + 100% Rec PK

T4-125% Rec P + 100% Rec NK

T5-150% Rec P + 100% Rec NK

T6-125% Rec K + 100% Rec NP

T7-150% Rec K + 100% Rec NP

The experiment was carried out in a CRD with three replications and was maintained for eight weeks. Destructive sampling was performed at weekly intervals, with samples collected from each set of containers for analysis. The physicochemical and chemical properties of the soil samples were analysed using standard procedures.

Initial characteristics of soil used in the study

The composite soil sample collected from the harvested rice field was found to be slightly alkaline (pH 7.69) and non-saline (EC: 0.51 dS m^{-1}). Textural analysis indicated that the soil had a clay loam texture.

The physical properties of the soil were as follows: bulk density (1.24 mg m^{-3}), particle density (1.99 mg m^{-3}), porosity (40.3 %) and water holding capacity (33.1 %). The organic carbon content was classified as 5.3 g kg^{-1}), while the cation exchange capacity was 16.1cmol (p$^+$) kg^{-1}. The available macronutrient status of the soil was as follows: high in K (195 kg ha^{-1}), medium in P (18 kg ha^{-1}) and low in N (190 kg ha^{-1}).

Results

Change in soil physico-chemical and macronutrient content as affected by varied levels of NPK under anaerobic conditions

Change in soil reaction (pH) **:** The addition of N at different levels (125 % and 150 % N + Rec PK) under submerged conditions significantly influenced the soil pH. The pH ranged from 6.23 to 7.89.

With respect to weekly intervals, the most significant changes in soil pH were observed at 14 DAI (D2), 21 DAI (D3) and 28 DAI (D4), recording values of 7.21, 7.26 and 7.25 respectively. A decreasing trend in soil pH was observed up to 28 DAI (D4), after which the pH gradually increased, approaching its initial value.

Among the treatments, the greatest significant reduction in soil pH (7.20 and 7.40) was recorded in 150 % N + Rec PK (T3), followed by 125 % N + Rec PK (T2) (Table 1).

About the interaction effect, a significant reduction in soil pH was observed in T3D2 (150 % N + Rec PK @ 14 DAI) and T2D2 (125 % N + Rec PK @ 21 DAI), with values of 6.23 and 6.46, respectively. The results indicate that excess P and K additions did not influence soil pH as significantly as excess N addition.

Change in soil salinity (EC)**:** The soil EC ranged from 0.51 to 1.39 dS m^{-1}. Regarding weekly intervals, an increase in soil EC was observed up to 28 DAI (D4), after which it gradually declined and stabilized by 56 DAI (D8). The highest significant increase in soil EC (0.98 dS m^{-1}) was recorded at 28 DAI (D4), followed by 35 DAI (D5). Conversely, the lowest EC value (0.59 dS m^{-1}) was observed in the final week of the study (D8). The EC value recorded at 14 DAI (D2) and 42 DAI (D6) were statistically on par with each other.

Among the NPK treatments, each level significantly influenced soil EC. The highest significant soil EC value (0.96 dS m^{-1}) was observed in 150 % K + Rec NP (T7), followed by 150 % P + Rec NK (T5) with 0.86 dS m^{-1}. The lowest soil EC value (0.59 dS m^{-1}) was recorded in 100 % NPK (T1), followed by 125 % N + Rec PK (T2) with 0.64 dS m-1. The results indicate that P and K @ 150 % significantly increased the soil salinity level.

Regarding the interaction effect, the highest soil EC value (1.39 dS m^{-1}) was recorded at T4D7 (150 % K + Rec NP @ 28 DAI), which was statistically significant. Additionally, the interaction effects of T5D4 (150 % P + Rec NK @ 28 DAI) and T6D4 (125 % K + Rec NP) were on par with each other (Table 2).

Change in KMNO$_4$-N: The soil available N content significantly increased with the application of higher levels of N. The data corresponds to the addition of varying levels of NPK fertilizers at different period of incubation. The available N was ranged from 194 kg ha^{-1} to 262 kg ha^{-1}, with the maximum available N (236 kg ha^{-1}) recorded at D3, which was found to be highly significant (Table 3). The lowest available N content was observed at D7 (201 kg ha^{-1}) and D8 (200 kg ha^{-1}).

During the initial weeks, the release of available N followed an increasing trend, reaching its peak at 28 DAI (D4). However, in the subsequent weeks, the available N content declined until 56 DAI (D4).

Among the treatments effects, soil treated with 150 % N + Rec PK (T3) recorded 243 kg ha^{-1}, followed by 125 % N + Rec PK (T2) with 227 kg ha^{-1}. In the balanced NPK (T1), the available N content was 212 kg ha^{-1}, which was on par with the excess P and K treatments.

Regarding the interaction effect, the maximum significant interaction was observed in T3D4 (150 % N + Rec PK @ 28 DAI), which was on par with T3D3 (150 % N + Rec PK @ 21 DAI) and T3D5 (150 % N + Rec PK @ 35 DAI). These findings indicate that excess N application significantly influenced with availability of N in the soil.

Change in Olsen-P: The available P content recorded in the treatments ranged from 19.30 to 54.83 kg ha^{-1}. A highly significant available P content of 30.35 kg ha^{-1} was observed at 21 DAI (D3), followed by 28 DAI (28.95 kg ha^{-1}). The lowest available P recorded at 49 DAI (20.81 kg ha^{-1}) and 56 DAI (kg ha $^{-1}$). The available P content increased up to 21 DAI (D3), after which a gradual decline was observed in the following weeks.

Table 1. Effect of varied levels of NPK on soil reaction at different periods of incubation under anaerobic condition

Treatments	7 DAI (D1)	14 DAI (D2)	21 DAI (D3)	28 DAI (D4)	35 DAI (D5)	42 DAI (D6)	49 DAI (D7)	56 DAI (D8)	Mean		SEd	CD @ 5%
T_1: 100%NPK	7.70	7.50	7.40	7.45	7.40	7.50	7.50	7.50	**7.49**	**D**	0.052	0.103
T_2 : 125%N +Rec PK	7.80	6.41	6.90	7.50	7.60	7.70	7.62	7.70	**7.40**			
T_3 : 150% N +Rec PK	7.45	6.23	6.46	6.94	7.34	7.76	7.75	7.67	**7.20**			
T_4 : 125%P +Rec NK	7.89	7.65	7.55	7.17	7.43	7.63	7.70	7.54	**7.57**	**T**	0.048	0.096
T_5: 150%P +Rec NK	7.71	7.67	7.54	7.01	7.53	7.83	7.63	7.73	**7.58**			
T_6 : 125%K +Rec NP	7.67	7.45	7.50	7.23	7.61	7.60	7.63	7.60	**7.54**			
T_7 : 150%K +Rec NP	7.60	7.58	7.50	7.42	7.58	7.80	7.60	7.64	**7.59**	**D ×T**	0.137	0.273
Mean	**7.68**	**7.21**	**7.26**	**7.25**	**7.50**	**7.69**	**7.63**	**7.63**	**7.48**			

Table 2. Effect of varied levels of NPK on soil EC at different periods of incubation under anaerobic condition

Treatments	7 DAI (D1)	14 DAI (D2)	21 DAI (D3)	28 DAI (D4)	35 DAI (D5)	42 DAI (D6)	49 DAI (D7)	56 DAI (D8)	Mean		SEd	CD @5%
T_1: 100%NPK	0.54	0.62	0.61	0.65	0.65	0.58	0.52	0.52	**0.59**	**D**	0.005	0.011
T_2 : 125%N +Rec PK	0.51	0.64	0.70	0.75	0.81	0.61	0.55	0.55	**0.64**			
T_3 : 150% N +Rec PK	0.55	0.70	0.85	1.02	0.96	0.78	0.57	0.52	**0.74**			
T_4 : 125%P +Rec NK	0.62	0.86	0.82	0.88	0.70	0.75	0.60	0.54	**0.72**			
T_5: 150%P +Rec NK	0.70	0.80	0.81	1.12	1.07	0.97	0.71	0.69	**0.86**	**T**	0.005	0.010
T_6 : 125%K +Rec NP	0.71	0.74	0.94	1.10	0.85	0.80	0.74	0.63	**0.81**			
T_7 : 150%K +Rec NP	0.85	0.91	1.21	1.39	1.02	0.85	0.78	0.70	**0.96**	**D ×T**	0.015	0.031
Mean	**0.64**	**0.75**	**0.84**	**0.98**	**0.86**	**0.76**	**0.63**	**0.59**	**0.76**			

Table 3. Effect of varied levels of NPK on $KMNO_4$-N at different periods of incubation under anaerobic condition

Treatments	7 DAI (D1)	14 DAI (D2)	21 DAI (D3)	28 DAI (D4)	35 DAI (D5)	42 DAI (D6)	49 DAI (D7)	56 DAI (D8)	Mean		SEd	CD @5%
T_1: 100%NPK	202	231	229	220	218	204	195	194	**212**	**D**	1.732	3.431
T_2 : 125%N +Rec PK	220	246	249	236	227	221	208	207	**227**			
T_3 : 150% N +Rec PK	247	251	260	262	255	236	218	215	**243**			
T_4 : 125%P +Rec NK	203	228	231	230	218	209	195	196	**214**			
T_5: 150%P +Rec NK	215	236	220	219	207	203	198	196	**212**	**T**	1.620	3.210
T_6 : 125%K +Rec NP	208	217	230	217	216	208	198	195	**211**			
T_7 : 150%K +Rec NP	212	220	236	231	219	205	198	194	**214**	**D ×T**	4.582	9.079
Mean	**215**	**233**	**236**	**231**	**223**	**212**	**201**	**200**	**219**			

The highest significant available P levels were recorded in the 150 % P + Rec NK (T5) and 125 % P + Rec NK (T4) treatments, with values of 37.55 mg kg^{-1} and 25.50 mg kg^{-1}, respectively (Table 4). Conversely, the lowest available P content of 21.43 kg ha^{-1} was observed in soil treated with 125 % K + Rec NP (T6). The available P in T1 (22.32 kg ha^{-1}) was on par with T2 (22.52 kg ha^{-1}) and T7 (22.12 kg ha^{-1}). Similarly, T3 (21.91 kg ha^{-1}) and T7 (22.12 kg ha^{-1}) were statistically comparable.

Regarding the interaction effects, the highest significant available P content of 54.83 kg ha^{-1} was recorded in T5D3 (150 % P + Rec NK @ 21 DAI), followed by T4D3 (32.07 kg ha^{-1}). The results indicate that the application of excess P (150 % and 125 %) significantly influenced available P levels.

Change in NH_4OAc-K **:** The available K content in soil treated with varying levels of NPK fertilizers was significantly influenced, ranging from 193 to 260 kg ha^{-1}. The highest significant available K content of 238 kg ha^{-1} was recorded at 21 DAI (D3) and 28 DAI (D4), while the lowest K content was observed at 49 DAI (204 kg ha^{-1}) and 56 DAI (202 kg ha^{-1}) (Table 5). The available K content exhibited an increasing trend until 28 DAI (D4), followed by a gradual decline until 56 DAI (D8).

Among the NPK treatments, potassium application at 150 % (T6) and 125 % (T7) resulted in significantly higher available K levels compared to other treatments. The highest available K content was recorded as 243 kg ha^{-1} in T6 and 234 kg ha^{-1} in T7. The soil treated with 100 % NPK (T1) and 150 % N + Rec PK (T3) showed statistically comparable results. The interaction effect was found to be non-significant.

Discussion

Impact of varied NPK levels on soil pH and salinity

In the present study, the addition of N at different levels under submerged conditions significantly influenced the soil pH. Under anaerobic condition, the application of urea led to a decrease in soil pH, with the most pronounced drop observed in excess N treatments (11). Among the treatments, the maximum reduction in soil pH was noticed in 150 % N + Rec PK (T3), followed by 125 % N + Rec PK (T2) respectively (Fig. 1).

A sharp decline in soil pH was observed at 14 days DAI, which may be attributed to the beginning of nitrification, involving ammonium oxidation and the H+ ions release (12). This pH decline was more pronounced in soils with excess N application. The decreasing trend in soil pH was noticed up to 28 DAI (D4), after which it gradually increased, reaching near initial values by 56 DAI. This rise in pH towards the end of the study could be due to the onset of nitrate denitrification, which neutralise the acidity.

Changes in soil pH under anaerobic conditions were found to be more significant than under aerobic conditions. Under submerged conditions, acidic soils tend to increase in pH, while alkaline soils approach neutrality (13). In the study, the initial soil pH was brought to neutral condition during the period of submergence. In contrast, excess P and K application did not significantly influence the soil pH; however, 0.2-to-0.6-unit decrease was observed in treatments with P and K additions (14).

Furthermore, the addition of P and K at 150 % increased salinity levels in soil. The highest significant soil EC value of 0.96 dS m^{-1} was recorded in the 150 % K + Rec NP (T7) treatment, followed by 150 % P + Rec NK (T5) at 0.86 dS m^{-1}. The lowest soil EC value of 0.59 dS m^{-1} was noticed in 100 % NPK (T1), followed by 125 % N + Rec PK (T2) at 0.64 dS m^{-1} (Fig. 2).

EC is measured by the ionic concentration in soil solution. Under anaerobic condition, the ionic strength increases with the accumulation of macro and micronutrients in the soil solution (15). Consequently, excess P and K applications led to a higher ion concentration into the soil solution compared to excess N. The increasing trend in soil EC continued until 28 DAI (D4), after which it gradually stabilized at 56 DAI (D8). Change in soil EC typically occur within the first three to four weeks following mineral fertilizer application under anaerobic condition (16).

Table 4. Effect of varied levels of NPK on Olsen-P at different periods of incubation under anaerobic condition

Treatments	7 DAI (D1)	14 DAI (D2)	21 DAI (D3)	28 DAI (D4)	35 DAI (D5)	42 DAI (D6)	49 DAI (D7)	56 DAI (D8)	Mean		SEd	CD @5%
T_1: 100%NPK	21.80	25.71	25.14	24.05	21.95	21.30	19.32	19.30	**22.32**			
T_2 : 125%N +Rec PK	19.78	24.50	25.58	25.12	24.00	22.18	19.48	19.50	**22.52**	**D**	0.198	0.393
T_3 : 150% N +Rec PK	19.30	21.15	24.80	25.06	23.85	22.14	19.58	19.42	**21.91**			
T_4 : 125%P +Rec NK	23.65	27.76	32.07	32.00	24.36	22.18	21.00	21.00	**25.50**			
T_5: 150%P +Rec NK	26.05	52.60	54.83	48.39	36.17	30.29	26.59	25.50	**37.55**	**T**	0.185	0.367
T_6 : 125%K +Rec NP	20.15	23.05	25.08	22.93	20.17	20.04	20.10	19.95	**21.43**			
T_7 : 150%K +Rec NP	19.76	22.84	25.00	25.11	23.00	22.09	19.65	19.50	**22.12**			
Mean	**21.49**	**28.22**	**30.35**	**28.95**	**24.78**	**22.88**	**20.81**	**20.59**	**24.76**	**D ×T**	0.524	1.039

Table 5. Effect of varied levels of NPK on NH_4OAc-K at different periods of incubation under anaerobic condition

Treatments	7 DAI (D1)	14 DAI (D2)	21 DAI (D3)	28 DAI (D4)	35 DAI (D5)	42 DAI (D6)	49 DAI (D7)	56 DAI (D8)	Mean		SEd	CD @5%
T_1: 100%NPK	210	221	229	231	218	204	195	194	**213**			
T_2 : 125%N +Rec PK	213	227	229	233	228	217	204	198	**219**	**D**	1.824	3.614
T_3 : 150% N +Rec PK	217	229	231	226	215	203	193	193	**213**			
T_4 : 125%P +Rec NK	219	225	237	238	218	207	195	196	**217**			
T_5: 150%P +Rec NK	215	236	234	230	226	215	197	196	**219**	**T**	1.706	3.380
T_6 : 125%K +Rec NP	236	240	246	249	241	228	218	210	**234**			
T_7 : 150%K +Rec NP	239	255	259	260	253	230	225	225	**243**			
Mean	**221**	**233**	**238**	**238**	**228**	**215**	**204**	**202**	**222**	**D ×T**	4.826	NS

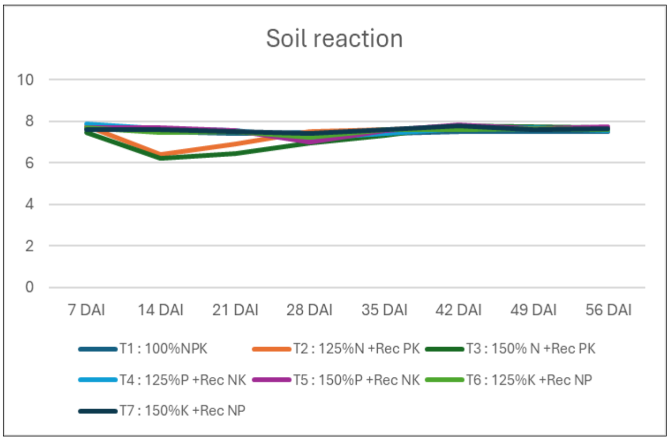

Fig. 1. Dynamic changing effect in soil reacction (pH) with varied levels of NPK fertilizers under submerged condition.

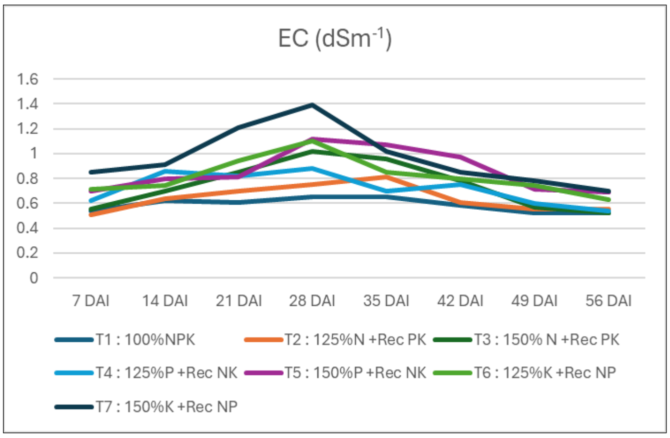

Fig. 2. Dynamic changing effect in soil salinity (EC (dSm^{-1})) with varied levels of NPK fertilizers under submerged condition.

A prolonged increase in salinity level due to excessive P or K application can potentially hinder biochemical processes by inhibiting anaerobic denitrifying bacterial activity. This inhibition may be attributed to the higher osmotic pressure in saline soils, as previously reported (17).

Impact of varied NPK levels on soil available NPK content

Flooding has a significant impact on nutrient availability, with some nutrients becoming more available under anaerobic conditions, while others are reduced due to fixation (18). In this study, N content significantly increased with higher levels of N application under anaerobic conditions. Among the treatments, 150 % N + Rec PK (T3) and 125 % N + Rec PK (T2) recorded 243 kg ha^{-1} and 227 kg ha^{-1} of available nitrogen, respectively, with both values being highly significant.

During the initial weeks, available N release followed an increasing trend up to 28 DAI (D4), after which a declining trend was observed until 56 DAI (D4) (Fig. 3). High nitrogen application (150 % N + Rec PK) lead to increased NH_4^+ accumulation in submerged soils, consistent with studies showing that nitrogen availability peaks around 28 DAI. The increase in N accumulation was attributed to the nitrification process, and in this study, the complete release of N from the applied fertilizer was observed within four weeks after incubation. Increasing the concentration of N to 150 % significantly increased the N availability in soil (19).

After nitrification process, N availability in flooded soils declines as it is lost through leaching and denitrification. Since leaching was not permissible in this study, denitrification was likely the primary biochemical reaction responsible for the observed decrease in available N at the end of the study (20). Another possible reason for the decrease in available N could be immobilization of microbes (21). Under anaerobic condition, the absence of oxygen slows down the activity of Nitrosomonas, which is responsible for ammonium oxidation, leading to NH^{4+} accumulation and altered nitrogen transformation. In soils treated with balanced NPK (T1), available N content was comparable to that in excess P and K treatments, indicating that P and K application did not affect nitrogen availability under anaerobic conditions (22, 23).

Frequent flooding and drainage cycles influence phosphorus transformation and availability in soil. In the present study, availability of P increased with higher P application levels. The highest available P content was recorded in 150 % P + Rec NK (T5), followed by 125 % P + Rec NK treatment (T4) (Fig. 4). The pronounced effect of P fertilization on high P availability and the linear response of P application to P availability were consistent with previous findings.

Under submerged conditions, a decrease in soil redox potential (Eh) enhances P availability (24). Prolonged submergence results in the accumulation of reducing conditions, which promotes P hydrolysis (25, 26). Soils treated with 100 % NPK and excess N or K released similar amounts of P, which was lower than that observed in excess P treatments. This may be attributed to synergistic interactions between macronutrients (27). The increase in available P was observed up to 21 DAI (D3), after which a decline was noted in all treatments. When P accumulation in the soil reaches a certain threshold, its release into floodwater stabilizes (28, 29). The observed reduction in available P may be due to microbial immobilization or fixation (30).

The highest available K content was recorded as 243 kg ha^{-1} and 234 kg ha^{-1} in 150 % K+ Rec NP (T7) and 125 % K+ Rec NP (T6), respectively. Flooding generally increases K availability in soil, as Fe^{2+} and Mn^{2+} ions, generated through soil reduction, displace Na^+, K^+, Ca^{2+} and Mg^{2+} from clay exchange sites. Additionally, concentration of the K in soil solution increases with higher K fertilizer application (31).

In anaerobic conditions, K availability peaks between two and three weeks after submergence and then gradually declines (32). When adequate nutrients were applied the availability of K also increased. The maximum K availability was recorded at 28 DAI (D4), after which a declining trend was observed until 56 DAI (D8) (Fig. 5). Potassium concentration in soil solution generally increases for three to four weeks following submergence (33), aligning with the findings of this study. The decline in K availability during the later stages of submergence may be due to K fixation within the soil exchange complex (34, 35).

In treatment with excess N and P application, K release remained comparable to that in balanced fertilized soil, indicating that excess N or P did not interfere with K availability under submerged condition (36).

Conclusion

Under anaerobic conditions, the release of available N, P and K was most pronounced between 21 and 28 DAI, coinciding with microbial activity and redox changes. High nitrogen application (150 % N + Rec PK) led to increased NH_4^+ accumulation in submerged soils, with peak nitrogen availability observed around 28 days DAI.

Higher P application (150 % P + Rec NK) significantly enhanced P availability by reducing adsorption to soil particles, as evidenced by the highest available P content in treatments with increased P levels. Unlike N and P, potassium does not undergo microbial transformations; its availability depends on soil mineralogy and exchange processes. In submerged conditions, exchangeable K increases due to higher input of K and changes in cation exchange capacity (CEC), leading to greater K release.

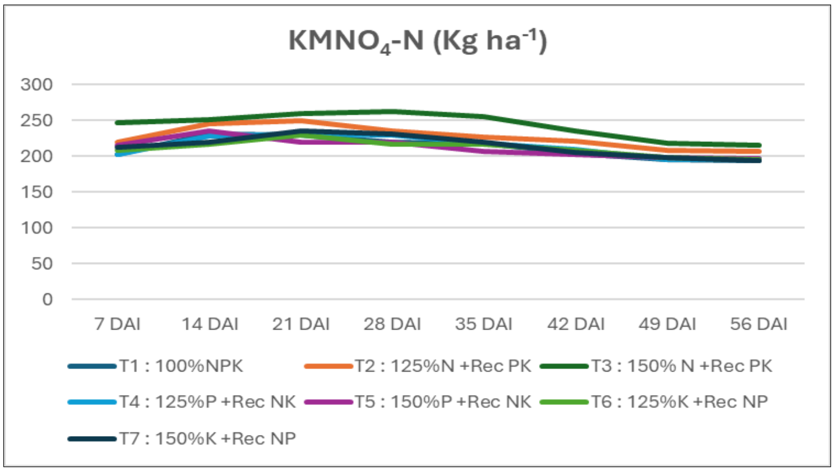

Fig. 3. Dynamic changing effect in $KMNO_4$-N (Kg ha^{-1}) with varied levels of NPK fertilizers under submerged condition.

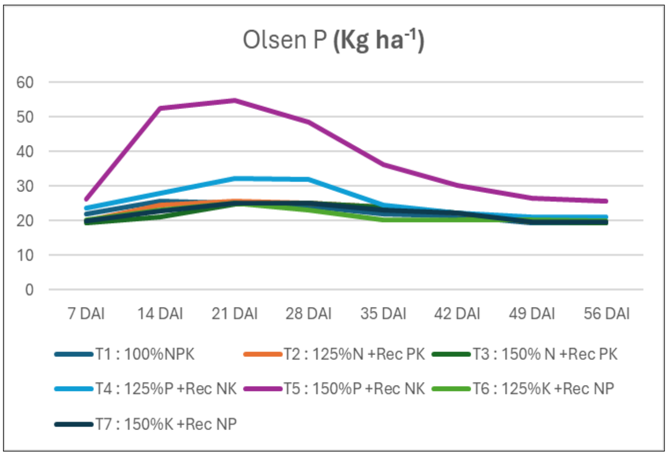

Fig. 4. Dynamic changing effect in Olsen-P (Kg ha^{-1}) with varied levels of NPK fertilizers under submerged condition.

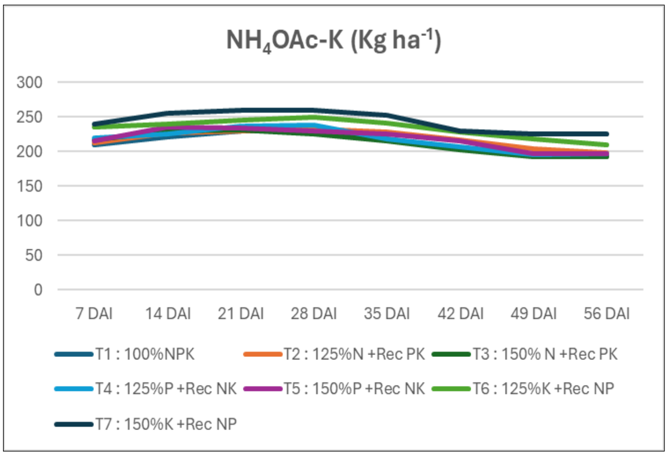

Fig. 5. Dynamic changing effect in NH_4OAc-K (Kg ha^{-1}) with varied levels of NPK fertilizers under submerged condition.

The study demonstrated that increasing NPK levels to 150 % significantly enhanced nutrient availability in the soil. Application of such levels of nutrients might be beneficial under nutrient-deficit conditions and could help mitigate yield reductions. However, further research is required to know the long-term impact of elevated NPK levels on soil properties, plant growth and yield attributes.

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Authors' contributions

KT, SV, JVH and VR, were involved in the conceptualization and participated in the methodology. KT conducted the formal analysis and investigation. SV and JVH was responsible for drafting and contributed to reviewing and editing. Investigation guidance was provided by VR. The first draft of the manuscript was written by KT and all authors provided comments on previous versions. All authors read and approved the final manuscript. Compliance with ethical standards

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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