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Effects of 42-year long-term fertilizer management on soil phosphorus availability, fractionation, adsorption–desorption isotherm and plant uptake in flooded tropical rice

Pratap Bhattacharyya[*], *Amaresh Kumar Nayak, Mohammad Shahid, Rahul Tripathi, Sangita Mohanty, Anjani Kumar, Rajagounder Raja, Bipin Bihari Panda, Banwari Lal, Priyanka Gautam, Chinmaya Kumar Swain, Koushik Singha Roy, Pradeep Kumar Dash*

Division of Crop Production, Central Rice Research Institute, Cuttack 753006, Odisha, India

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ABSTRACT

Soil phosphorus (P) fractionation, adsorption, and desorption isotherm, and rice yield and P uptake were investigated in flooded tropical rice (*Oryza sativa* L.) following 42-year fertilizer and manure application. The treatments included low-input [unfertilized control without N, P, or K (C_0N_0)], farmyard manure (FYM) (C_1N_0), NP (C_0NP), NPK (C_0NPK), FYM + NP (C_1NP), and high-input treatment, FYM + NPK (C_1NPK). Grain yield was increased significantly by 74% over the control under the combined application of FYM + NPK. However, under low- and high-input treatments, yield as well as P uptake was maintained at constant levels for 35 years. During the same period, high yield levels and P uptake were maintained under the C_0NP, C_0NPK, and C_1NPK treatments. These are unique characteristics of a tropical flooded ecosystem, which is a self-sustaining system for rice production. The Fe–P fraction was highest compared to the Ca–P and Al–P fractions after 42 years of fertilizer application and was significantly higher under FYM + NPK treatment. The P adsorption capacity of soil was highest under the low-input treatment and lowest under long-term balanced fertilization (FYM + NPK). In contrast, P desorption capacity was highest under NPK and lowest in the control treatment. Long-term balanced fertilization in the form of FYM + NPK for 42 years lowered the bonding energy and adsorption capacity for P in soil but increased its desorption potential, increasing P availability to the plant and leading to higher P uptake and yield maintenance.

1. Introduction

Long-term experiments provide a means of evaluating sustainable management systems in agriculture [1]. Several long-term fertilizer experiments have been conducted to quantify changes in major and trace elements in soils [2]. Phosphorus (P) deficiency is a universal constraint to crop production and constitutes the second most important soil

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[*] Corresponding author.
E-mail address: pratap162001@yahoo.co.in (P. Bhattacharyya).
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fertility problem throughout the world [3]. Crop yields are often limited by low P availability in soils, owing mainly to adsorption and precipitation reactions of both indigenous soil P and applied fertilizer P with iron (Fe), aluminum (Al), or calcium (Ca) [4]. Low P uptake efficiency of plants is associated primarily with limited P availability in native soil. Consequently, large amounts of expensive inorganic P fertilizers need to be applied to many agricultural soils to attain reasonable crop yields [5]. Application of organic matter to soil increases P solubility, decreases P fixation, and thus improves P availability to plants [4].

Several additive mechanisms may be involved, including the release of inorganic P from decaying residues, blockage of P sorption sites by organic molecules released from the residues, regulation of soil pH, and complexation of soluble Al and Fe by organic molecules [6]. The adsorption behavior of P in a soil system can be determined by analysis of the adsorption data for various isotherms using equations such as the Langmuir and Freundlich equations. The P concentration in soil depends on P adsorption on the surface of soil colloids. The P availability in soil depends on the degree of P adsorption on soil colloids [7,8].

The interaction of N with P is the single most important nutrient interaction [9]. When P input from fertilizer exceeds P output in crop, P accumulates in soil over time [10]. The information obtained from P fractionation schemes has been used to estimate the fate of applied P and the relationship between forms of P and plant P nutrition [11]. Thus, for developing long-term P management strategies, it is important to ascertain the forms and characteristics of P remaining in the soil after repeated fertilizer P application in an agroecosystem.

Soil inorganic P (Pi) represents the dominant component in the soil P pool, accounting for about 75–85% of soil total P [12]. Soil Pi is represented as various fractions such as Ca–P (HCl-extractable P), Fe- and Al–P (non-occluded Fe- and Al-bound P) and O–P (P occluded within Fe oxides) [13]. Sequential Pi fractionation distinguishing labile (resin-extractable P and $NaHCO_3$-extractable P) and more stable forms (Ca–P, Al–P, Fe–P, and O–P) of Pi has been established [14]. Ca–P is generally not fractionated further into subfractions because the Ca–P fraction in non-calcareous soils is rather small [15].

However, in calcareous soils, most Pi is present in various Ca-bound forms and there are great differences in P availability among these Ca–P fractions. Huang et al [16] investigated the soil P dynamics in paddy soils in a one-season field experiment. In contrast, information about the dynamics of soil Pi fractions and P transformation under long-term fertilization in relation to adsorption and desorption isotherms is sparse. The objectives of the present study were (1) to investigate the yield and P uptake of rice in response to long-term fertilization, (2) to investigate long-term fertilization effects on soil P fractions, and (3) to evaluate P adsorption and desorption isotherms in flooded rice soil after long-term fertilizations.

2. Materials and methods

2.1. Experimental site

A long-term fertilizer experiment has been continuing since 1969, involving a rice–rice cropping system in tropical Aeric Endoaquept soil on the experimental farm of the Central Rice Research Institute, Cuttack. The site is located in the alluvial tract of the Mahanadi basin at 20°25′ N and 85°55′ E at an altitude of 24 m.a.s.l. in eastern India. The climate is tropical with mean annual precipitation around 1500 mm and the predominant rainfall occurs from June to September. The soil is sandy clay loam (30.9% clay, 16.6% silt, 52.5% sand) with bulk density 1.41 Mg m^{-3}, pH (using 1:2.5, soil:water suspension) 6.6, total C 0.78%, and total N 0.08%. The cation exchange capacity is 15.2 cmol (P+) kg^{-1} and the available P content of the initial soil was 13 mg kg^{-1}.

2.2. Crop establishment and treatments

The field experiment was conducted for 42 years (there was no crop in the dry season during 1984–1993) under rice–rice cultivation and the six treatments under the study were replicated three times in a randomized block design. The field was plowed thoroughly and flooded for puddling and leveling 2–3 days before transplanting. Rice seedlings around 25 days old were transplanted at a spacing of 20 cm × 15 cm with two to three seedlings per hill in both wet (July–December) and dry (January–April) seasons. Farmyard manure was applied to the field once yearly during wet season at 5 t ha^{-1}. The total C and P content in the FYM was 245 g kg^{-1} and 3.7 g kg^{-1}, respectively. Nitrogen was applied in the form of 50% urea as basal and the rest in two equal splits as topdressing after transplanting. Topdressing with N fertilizer (urea) was performed at maximum tillering and panicle initiation stage of crop growth in both wet and dry seasons. The full doses of P and K were applied as basal just before transplanting in the form of single superphosphate and muriate of potash (KCl). All the field plots remained continuously flooded to a depth of 7 ± 3 cm during the entire period of crop growth and were drained 10 days before harvest. The crop was cultivated according to local recommended agronomic practices except for the fertilization, which was performed as described for the treatments. The treatments were as follows:

(a) Control (with no fertilizers or organic manures) (C_0N_0)
(b) FYM (5 t ha^{-1} applied only in wet season) (C_1N_0).
(c) N + P (60 kg N ha^{-1} in wet season; 80 kg N ha^{-1} in dry season and 30 kg P_2O_5 ha^{-1} in wet season; 40 kg P_2O_5 ha^{-1} in dry season) (C_0NP)
(d) NPK (60 kg N ha^{-1} in wet season; 80 kg N ha^{-1} in dry season; 30 kg P_2O_5 ha^{-1} in wet season; 40 kg P_2O_5 ha^{-1} in dry season and 30 kg K_2O ha^{-1} in wet season; 40 kg K_2O ha^{-1} in dry season) (C_0NPK)
(e) FYM + NP (5 t ha^{-1} + 60 kg N ha^{-1} in wet season; 80 kg N ha^{-1} in dry season and 30 kg P_2O_5 ha^{-1} in wet season; 40 kg P_2O_5 ha^{-1} in dry season) (C_1NP).
(f) FYM + NPK (5 t ha^{-1} + 60 kg N ha^{-1} in wet season; 80 kg N ha^{-1} in dry season; 30 kg P_2O_5 ha^{-1} in wet season; 40 kg P_2O_5 ha^{-1} in dry season and 30 kg K_2O ha^{-1} in wet season; 40 kg K_2O ha^{-1} in dry season) (C_1NPK).

2.3. Soil sampling and storage

Soil samples were collected in three replications with an auger (at a depth of 0–15 cm) in both wet and dry seasons