

Assessment of phosphorus and zinc dynamics in a rice growing soil of North-Eastern India under contrasting moisture regimes

Tathagata Karmakar

Rohit Kumar Choudhury

rkrchoudhury.ssac1998@gmail.com

Bidhan Chandra Krishi Viswavidyalaya: Bidhan Chandra Krishi Viswa Vidyalaya <https://orcid.org/0009-0000-7544-3752>

Dibyendu Mukhopadhyay

Sumana Balo

Sayan Debsingha

Ganesh Chandra Banik

Ranjan Bhattacharyya

Research Article

Keywords: Nutrient dynamics, Yield prediction; P×Zn interaction; Soil moisture regime, Adsorption, Management

Posted Date: September 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10741998/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Assessment of phosphorus and zinc dynamics in a rice growing soil of North-Eastern India under contrasting moisture regimes

Tathagata Karmakar¹, Rohit Kumar Choudhury^{2*}, Dibyendu Mukhopadhyay¹, Sumana Balo³, Sayan Debsingha¹, Ganesh Chandra Banik¹, and Ranjan Bhattacharyya⁴

¹Department of Soil Science and Agricultural Chemistry, Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar, West Bengal – 736165, India.

²Department of Agricultural Chemistry and Soil Science, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal – 741252, India.

³Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences (IAS), Siksha O Anusandhan (Deemed to be University), Bhubaneswar, Khorda, Odisha – 751029, India.

⁴Division of Environmental Sciences, ICAR-Indian Agricultural Research Institute, New Delhi – 110012, India.

***Corresponding Author's Email:** rkrchoudhury.ssac1998@gmail.com (**ORCID id:** <https://orcid.org/0009-0000-7544-3752>)

Abstract:

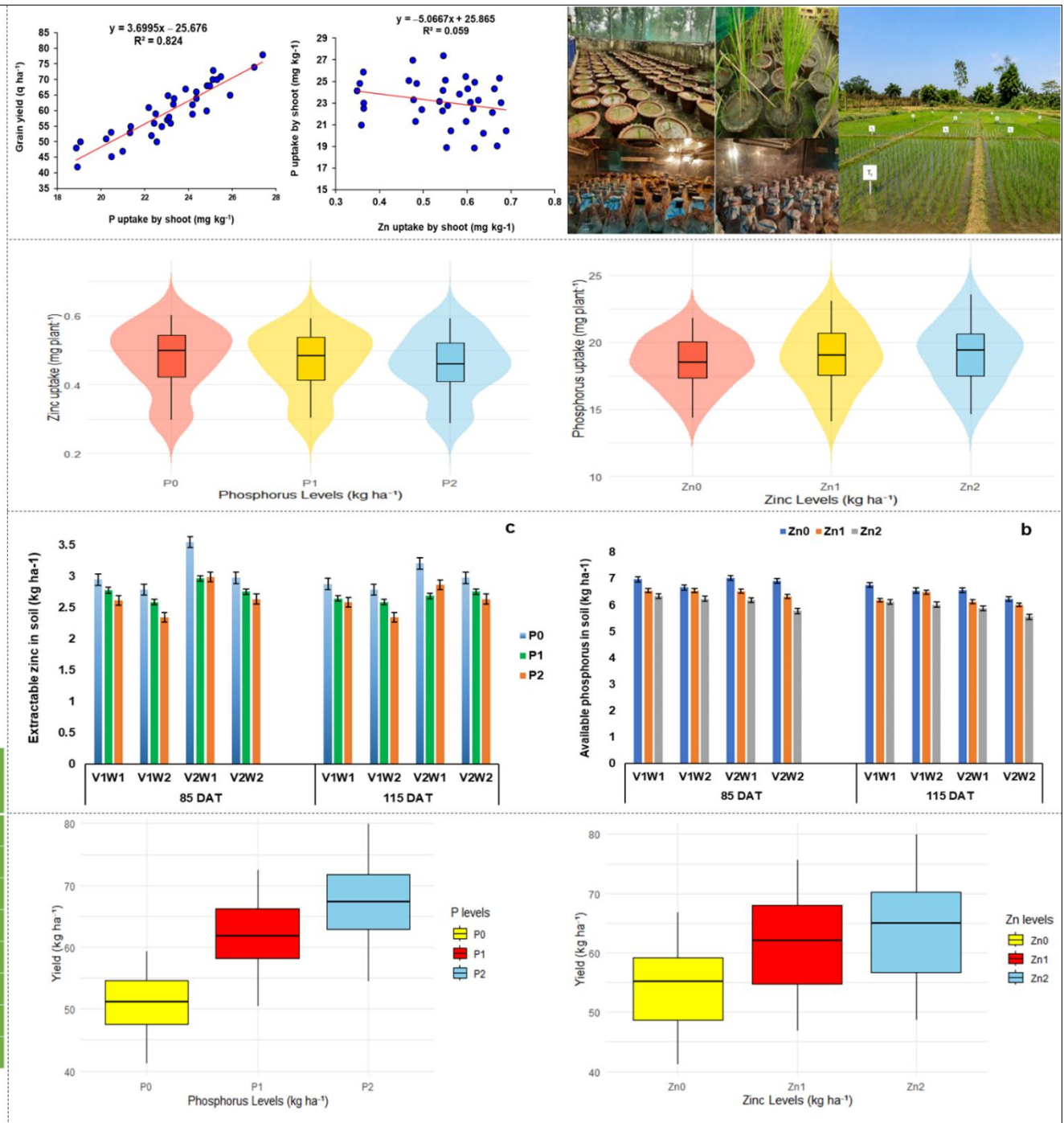
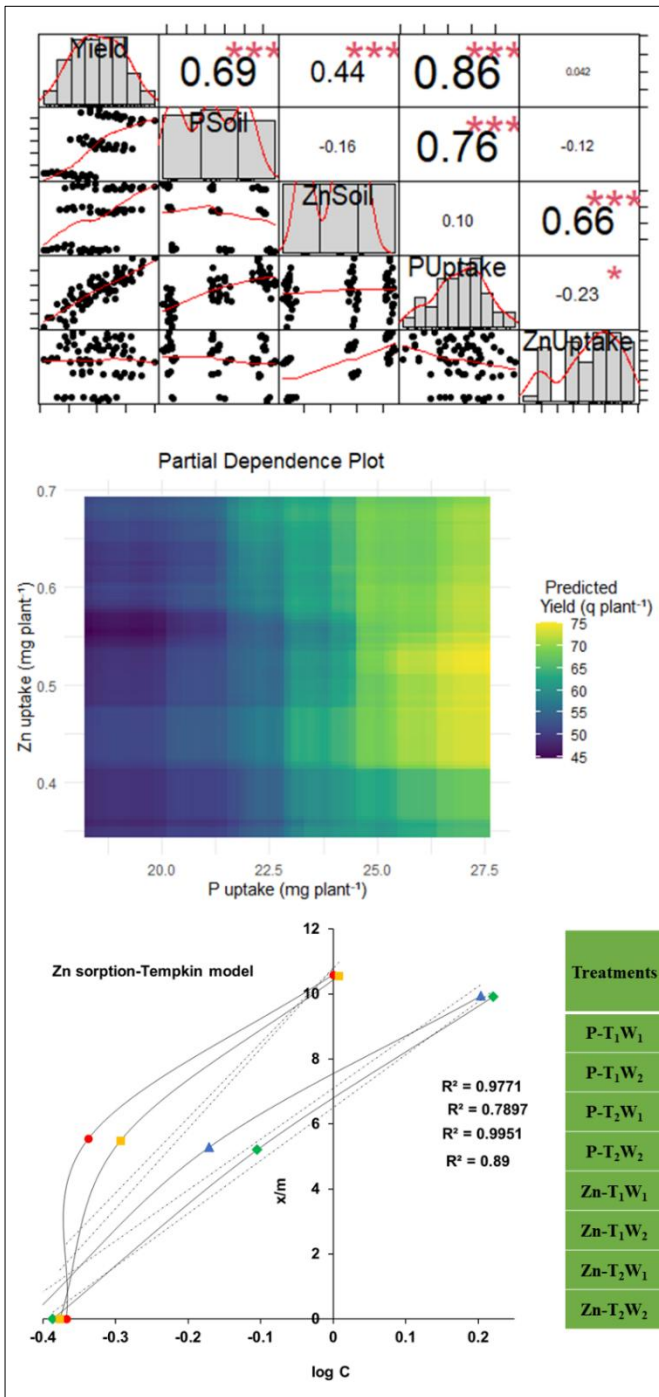
Aims: Understanding phosphorus (P) and zinc (Zn) interaction on plant response under contrasting moisture regimes is crucial for optimizing nutrient management in rice growing soils. The current study investigated the effects of graded P and Zn application on their dynamics within soil-plant continuum and finally on predicting grain yield under continuous flooding (W_1) and 50% of maximum water-holding capacity (W_2) using two rice cultivars DRR Dhan 45 (V_1) and IR 64 (V_2).

Methods: Pot and field experiments were conducted for two consecutive years (2023-2024 & 2024-2025) followed by batch sorption studies to elucidate the mechanisms governing P and Zn dynamics under different moisture and temperature regimes.

Results: P application significantly enhanced soil available P, P uptake, and grain yield, whereas Zn fertilization markedly increased Zn availability and uptake. Although P application reduced Zn availability and uptake, Zn application caused only a marginal decline in P availability in soil without adversely affecting P uptake and yield. The highest grain yield (78 q ha^{-1}) was obtained with the combined application of 60 kg P ha^{-1} and 25 kg Zn ha^{-1} under continuous flooding for cultivar IR 64 ($P_2Zn_2W_1V_2$), demonstrating the complementary effects of adequate P and Zn nutrition. Sorption studies revealed that P adsorption was best described by the Dubinin–Radushkevich model, whereas Zn adsorption followed the Temkin isotherm. Continuous flooding reduced the binding energy, thereby enhancing nutrient availability, while enhanced temperature strengthened adsorption, particularly for P, indicating a better nutrient retention under warmer conditions. Thermodynamic analysis showed that Zn adsorption was spontaneous, whereas P adsorption was non-spontaneous under the experimental conditions.

Conclusion: Overall, the study demonstrated that P nutrition was the principal driver of productivity in acidic *Terali* soils, while adequate Zn nutrition complements P utilization with only negligible antagonistic effects. These findings provide a mechanistic basis for optimizing P–Zn fertilization strategies under changing moisture and temperature regimes to sustain rice productivity.

Keywords: Nutrient dynamics, Yield prediction; P×Zn interaction; Soil moisture regime, Adsorption, Management



1 Introduction:

2 Rice (*Oryza sativa* L.) is the staple food for more than half of the world's population and contributes substantially
3 to global food and nutritional security by supplying approximately 21% of dietary energy and 15% of dietary
4 protein (Maclean et al., 2002). In India, particularly in the eastern Indo-Gangetic plains, rice cultivation is
5 predominantly concentrated in lowland ecosystems characterized by prolonged flooding and high annual rainfall.
6 The Terai region of West Bengal is one of the major rice-growing areas of eastern India, where strongly acidic
7 soils frequently limit crop productivity because of multiple nutrient constraints, particularly phosphorus (P) and
8 zinc (Zn) deficiencies (Alloway, 2009; Ganeshamurthy et al., 2016). As both nutrients play indispensable roles in
9 plant metabolism, their inadequate availability substantially reduces crop growth, nutrient use efficiency, and
10 grain yield.

11 Phosphorus is an essential macronutrient involved in energy transfer, photosynthesis, nucleic acid synthesis,
12 membrane formation, and numerous enzymatic processes. Despite its abundance in many agricultural soils, only
13 a small proportion remains available for plant uptake because phosphate ions are rapidly immobilized through
14 adsorption or precipitation with iron (Fe), aluminium (Al), and calcium (Ca) compounds, particularly under acidic
15 soil conditions (Dotaniya et al., 2015; Dey et al., 2017). Consequently, phosphorus deficiency continues to be one
16 of the principal nutritional limitations affecting rice production worldwide. Zinc, although required in
17 comparatively small quantities, is equally indispensable for normal plant growth owing to its involvement in
18 enzyme activation, protein synthesis, chlorophyll formation, auxin metabolism, and antioxidant defence
19 mechanisms. Zinc deficiency is estimated to affect nearly half of the world's paddy soils, with Asia accounting
20 for approximately one-third of the affected area. Deficiency of either nutrient adversely affects physiological
21 functions, restricts biomass accumulation, and ultimately reduces grain yield. The interaction between phosphorus
22 and zinc in soils and plants is highly complex. Numerous studies have demonstrated that excessive phosphorus
23 application may reduce Zn availability by enhancing Zn adsorption, promoting the formation of sparingly soluble
24 zinc phosphate compounds, or altering rhizosphere chemistry (Haldar and Mandal, 1981; Barrow, 1984).
25 Conversely, zinc availability may also influence phosphorus acquisition through modifications in root growth,
26 membrane transport, and enzyme activity. The magnitude and direction of this interaction depend on several soil
27 properties, including pH, organic matter, clay mineralogy, oxide content, and fertilizer management. Therefore,
28 balanced phosphorus and zinc fertilization is increasingly recognised as an effective strategy for sustaining crop
29 productivity while minimizing nutrient antagonism. Soil moisture and temperature further regulate the availability
30 and adsorption behaviour of both nutrients, particularly in flooded rice ecosystems. Under submerged conditions,
31 microbial reduction of ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}) dissolves iron oxides that previously adsorbed
32 phosphate, thereby increasing phosphorus availability in the soil solution (Sanyal and De Datta, 1991; Maranguit
33 et al., 2017; González et al., 2022). Consequently, phosphorus availability generally increases during prolonged
34 flooding following an initial period of immobilization. In contrast, zinc availability frequently declines under
35 anaerobic conditions owing to the formation of relatively insoluble compounds such as zinc sulphide (ZnS), zinc
36 carbonate (ZnCO_3), zinc hydroxide [$\text{Zn}(\text{OH})_2$], and zinc ferrite (ZnFe_2O_4), thereby increasing the risk of Zn
37 deficiency in submerged rice (Vodyanitskii, 2010; Gao et al., 2012; Abdullah et al., 2015; Fatehi et al., 2021).
38 Temperature exerts an additional influence by modifying sorption kinetics, reaction equilibria, and diffusion

processes, thereby affecting both phosphorus fixation and zinc adsorption (Wasewar et al., 2008; Huang et al., 2011; Jodeh et al., 2015; Xie et al., 2019). Although the individual behaviour of phosphorus and zinc under flooded conditions has been extensively investigated, comparatively few studies have simultaneously evaluated their interactions across contrasting moisture regimes while integrating nutrient uptake, adsorption characteristics, thermodynamic behaviour, and crop performance. Furthermore, limited information is available regarding the combined influence of phosphorus and zinc fertilization on nutrient dynamics in the acidic *Terai* soils of eastern India, where alternating flooding and moisture stress are becoming increasingly common under changing climatic conditions. Understanding these interactions is essential for developing balanced nutrient management strategies that maximise nutrient use efficiency while sustaining rice productivity. We hypothesised that balanced phosphorus and zinc fertilization would alleviate nutrient antagonism and improve nutrient uptake under both submerged and moisture-limited conditions, whereas soil moisture and temperature would substantially regulate their adsorption behaviour and subsequent bioavailability. Therefore, the objectives of the present investigation were to: (i) evaluate the effects of phosphorus and zinc fertilization on soil nutrient availability, plant nutrient uptake, and grain yield under contrasting moisture regimes using two rice cultivars; and (ii) investigate the adsorption behaviour of phosphorus and zinc under different moisture and temperature conditions using adsorption isotherm modelling to elucidate the mechanisms governing nutrient retention and availability in an acidic *Terai* soil of eastern India.

Materials and Methods:

Experimental site:

A pot experiment was carried out within a greenhouse of Uttar Banga Krishi Viswavidyalaya in Pundibari, Coochbehar, West Bengal, India. The soils were collected from 26.3938° N latitude and 89.3832° E longitude with an average altitude of 43 m belonging to Hills and *Terai* zone of West Bengal. The field experiment also had been conducted at the same site just beside the greenhouse.

Details of the pot experiment:

The pot experiment was carried out in earthen pots of 40 cm × 20 cm × 20 cm size during two consecutive *rabi* seasons 2023-2024 and 2024-2025 considering two different rice cultivars, DRR Dhan 45 (V_1) and IR 64 (V_2) (Fig.1). Surface soils (0-10 cm depth) were collected from new greenhouse area near Coochbehar Krishi Vigyan Kendra and 5 kg soils were distributed in each pot. The pot experiment was laid out in a Completely Randomized Design (CRD) and replicated thrice. The recommended dose of fertilizer (RDF) for that area was N:P₂O:K₂O:Zn::120:60:60:25 based on which the fertilizer treatments were given. Three different levels of P (0, 45 and 60 kg ha⁻¹) coupled with three different levels of Zn (0, 12.5 and 25 kg ha⁻¹) were applied in the form of single super phosphate and zinc sulphate (ZnSO₄.7H₂O) respectively (Table 1). Nitrogen (N) and potassium (K) were applied in the form of urea and muriate of potash, respectively. Full doses of P and K along with 1/2th dose of the N were given to each pot before transplantation of rice seedlings and the remaining nitrogen were given in two equal splits at 21 days intervals. There were 4 plants in each pot and after transplanting, some of the pots were submerged with water (W_1) and maintained throughout experiment and some pots were subjected to watering at 50% of maximum water holding capacity (W_2) level.

Details of the field experiment:

The field experiment was conducted during the *rabi* (winter) season of the year 2024-2025 at the experimental field of Uttar Banga Krishi Viswavidyalaya, Coochbehar, India considering the similar rice cultivars (Fig.1). It was laid out in a Factorial Randomized Block Design (FRBD) replicating thrice. All the treatment details as well as fertilizer recommendations remained same as of the pot experiment (Table 1). Full doses of P and K along with 1/2th dose of the N were given to each plot before transplantation of rice seedlings and the remaining nitrogen were given in two equal splits at 21 days intervals.

Processing and analysis of soil samples:

The soils samples were collected at two different crop growth stages, maximum tillering stage (85 DAT) and maturity (115 DAT) from 0-15 cm depth. Soil samples, collected from each plot, were shade-dried under air. The air-dried samples were manually crushed, passed through a 2 mm sieve, and finally subjected to the further laboratory analysis to characterize the key physico-chemical properties as per standard protocols, as outlined in Table S.1.

Analysis of plant samples:

In the both stages 3-5 rice hills from each pot were taken for bio-chemical analysis. At the stage of maturity both the vegetative along with reproductive parts of rice plant were collected and processed together to obtain total shoot uptake. Collected plant samples were washed first in running tap water, followed by dilute hydrochloric acid (HCl) solution and finally with deionized water. The plant materials were dried first in air and then in oven at 70°C to a constant weight and were then ground with the help of a stainless-steel mechanical grinder. 0.5 g of powdered plant/grain sample was digested using a tri-acid mixture (HNO₃: H₂SO₄: HClO₄ = 10:1:4) (Sarkar et al., 2016; Sparks et.al., 2006). Next, the digests were diluted and subjected to laboratory analysis to determine total N, P, K, and Zn concentration (Table S.1). The Nutrient Uptake (NU) in shoot was estimated from the equation provided below (Godebo et al., 2021):

$$\text{Nutrient Uptake (mg/plant)} = \frac{\text{Concentration of nutrient in shoot part (\%)} \times \text{dry weight of shoot part (mg/plant)}}{100}$$

....Eq.1

Incubation study for the sorption experiment:

An incubation study (batch experiment) was conducted to assess the sorption characteristics of phosphorus and zinc in the soil system. 3 g of initial soils were taken in conical flasks and treated with 30 ml of three different doses of phosphorus solution 0, 20.09 ppm (equivalent to 40 kg P ha⁻¹) and 26.79 ppm (equivalent to 60 kg P ha⁻¹) separately and kept inside an incubator for seven days (Fig.1). Similarly, three different doses of zinc 0, 5.58 ppm (equivalent to 12.5 kg Zn ha⁻¹), 11.16 ppm (equivalent to 25 kg Zn ha⁻¹) were treated with another three sets of soil samples kept in conical flasks and subjected to incubation for seven days. The moisture level for each sample was maintained as 100% (W₁) and 50% of maximum water holding capacity (W₂) with maintaining a constant temperature of 25°C (T₁) and at 35°C (T₂). On expiry of the incubation periods, the soil analysed for available Phosphorus (Bray and Kurtz, 1945) and DTPA-extractable Zinc (Lindsay and Norvel, 1978).

Adsorption isotherm modeling of Phosphate and Zinc:

Data collected regarding the amount of Phosphate and zinc (Zn) adsorbed by the unit weight of soil (x/m) and the equilibrium concentration of P and Zn concentrations in soil solution were fitted to four adsorption isotherm models at both 25°C and 35°C temperatures: i) Freundlich isotherm, ii) Langmuir isotherm, iii) Tempkin isotherm, and iv) Dubinin–Radushkevich isotherm (Table S.2). The amount of ions got disappeared from the soil solution was considered to be adsorbed on the surface of solid phase and calculated by the following equation (Singh et al., 2020):

$$\left(\frac{x}{m}\right) = \frac{(C_i - C_e)}{w} V \quad \dots \text{Eq.2.}$$

Where, $\frac{x}{m}$ is the amount of phosphate or zinc been adsorbed from soil solution by the unit weight of soil (mg g^{-1})

C_o is the initial concentration of phosphate or zinc ion in solution (mg l^{-1})

C_e is concentration of phosphate or zinc ion in equilibrium solution after adsorption (mg l^{-1})

V is the volume of the equilibrium solution (l)

w is the weight of the soil sample taken (g)

a. Freundlich isotherm:

This isotherm can be expressed as (Mabuza et al., 2022; Freundlich, 1926):

$$\frac{x}{m} = K_F C^{\frac{1}{n}} \quad (n > 1) \quad \dots \text{Eq.3}$$

where, x/m denotes the amount of adsorbate per unit quantity of adsorbent ($\mu\text{g g}^{-1}$), C means Equilibrium concentration of ions present in soil solution, K_F can be considered as Freundlich constant related to adsorption capacity and n is Freundlich constant related to adsorption intensity and $1/n$ indicates the function of sorption strength as well as surface heterogeneity factor (Dada et al., 2012). Freundlich isotherm is strictly empirical in nature (Habte et al., 2020). The outcome primarily relies on the provided adsorption process and the study's temperature conditions. The constant K_F was adopted as a theoretical indicator of the amount of phosphorus or zinc adsorbed from a solution with a standardized equilibrium concentration. The Freundlich equation, initially empirical in nature, aligns with a model of adsorption wherein the affinity (bonding energy) factor diminishes exponentially as the adsorption quantity expands (Sposito, 1980). The linear (logarithmic) transform of this equation is provided below (Mabuza et al., 2022):

$$\log \left(\frac{x}{m}\right) = \log K_F + \frac{1}{n} \log C \quad \dots \text{Eq.4}$$

The parameters K_F and n are specific to the sorbent-sorbate system and can usually be derived by fitting sorption data using linear regression (de la Rosa et al., 2008) and can be determined from the intercept and inverse of the slope from the $\log(x/m)$ vs $\log C$ plot respectively. The factor $1/n$ can also act as a heterogeneity parameter, with smaller values showing greater heterogeneity. The higher values of K_F indicates a better retention strength as well as a better sorption ability of the solid phase (Zhao and Selim, 2010). Similarly, with decreasing the values of the constant $1/n$ or increase in the values of n , the strength of adsorption becomes higher which indicates a stronger

bond between the adsorbent and the adsorbate. For a normal adsorption, $1/n$ always ranges between 0 and 1. The value of $1/n$ closer to zero suggests the more surface heterogeneity as well as heterogeneous adsorption and when it becomes unity the equation becomes a linear expression. If the value attains more than unity, it indicates cooperative adsorption or physisorption and less than one suggests chemisorption (Singh and Kumar, 2018). So, n values between 1 to 10 denote favourable sorption. The K_F and $1/n$ values determine the nature of the curvature and steepness of the curve (Habte et al., 2020).

b. Langmuir isotherm:

The Langmuir isotherm can be written as (Chen, 2015; Langmuir, 1918):

$$\left(\frac{x}{m}\right) = \frac{Q_m K_L C}{1 + K_L C}$$

....Eq.5

where, x/m denotes the amount of adsorbate per unit mass of adsorbent at any instant ($\mu\text{g g}^{-1}$), C means Equilibrium concentration of ions present in soil solution, Q_m indicates Langmuir adsorption maxima forming a monolayer on the homogenous surface of adsorbent ($\mu\text{g g}^{-1}$), K_L is the Langmuir constant related to binding energy (L mol^{-1}). The nature of the adsorption is favourable if $0 < R_L < 1$, unfavourable when $R_L > 1$, irreversible when $R_L = 0$ or linear when $R_L = 1$ (Zhou et al., 2017). Langmuir adsorption isotherm can provide a quantitative estimation of the monolayer formation by the adsorbate on the homogenous outer surface of an adsorbent as well as the adsorption maximum, after that no sorption occurred. Here in this model, the energy of adsorption is assumed to be remained constant during the sorption and the surface of the adsorbent contains a fixed number of adsorption sites available for binding molecules. At this experiment, this model has been employed to assess the equilibrium distribution of ions (e.g. phosphate and zinc) between exchanger and exchanging medium. The linear (logarithmic) transform of Langmuir equation can be expressed as below (Sanyal, 2018):

$$\left(\frac{C}{x/m}\right) = \frac{1}{Q_m K_L} + \frac{C}{Q_m}$$

....Eq.6

The values of the Langmuir parameters e.g. K_L and Q_m can be determined from the intercept and inverse of the slope from the $(C/x/m)$ vs $1/Q_m$ plot respectively.

c. Tempkin isotherm:

The non-linear expression of Tempkin adsorption isotherm can be written as (Atugoda et al., 2021):

$$\left(\frac{x}{m}\right) = \frac{RT}{b_T} \ln(A_T C) \quad \dots \text{Eq.7}$$

$$\Rightarrow \left(\frac{x}{m}\right) = B_T \ln(A_T C) \quad \dots \text{Eq.8}$$

Where, $\frac{RT}{b_T} = B_T$ which is a dimensionless constant related to the heat of adsorption (J mol^{-1}); x/m represents the amount of adsorbate per unit mass of adsorbent, C is equilibrium P or Zn concentration in soil solution, R is the

Universal gas constant (8.314 J/mol K), T indicates Absolute temperature, A_T represents a constant related to maximum binding energy ($L\ g^{-1}$), b_T represents Tempkin isotherm constant (Al-Wahbi and Dammag 2011). Tempkin isotherm is based on the hypothesis that the bonding energy or heat of the adsorption process, which is a function of temperature, decreases linearly with increase in the extent of surface coverage rather than logarithmic trend and considers the complex interaction between adsorbent and adsorbate. The simple logarithmic transformation of Tempkin isotherm can be expressed as (Sanyal and De Datta, 1991):

$$\left(\frac{x}{m}\right) = 2.303 \frac{RT}{b_T} \log A_T + 2.303 \frac{RT}{b_T} \log C \quad \dots \text{Eq.9}$$

The Tempkin isotherm parameters e.g. b_T and A_T can be calculated from slope and intercept of the (x/m) vs. $\log C$ plot. In some cases, the linear transformed Tempkin plots may produce gentle curves rather than a straight line when implemented practically with field data (Sanyal, 2018).

d. Dubinin–Radushkevich (D-R) isotherm:

The Dubinin-Radushkevich (D-R) isotherm is also a well-established empirical isotherm model primarily used to assess the sorption equilibria of gases on both homogenous and heterogeneous surfaces of microporous solids such as zeolites, activated carbon etc with a Gaussian energy distribution (Gunay et al., 2007). The model is rooted in the notion that adsorption in micropores occurs through filling of the pore volume, not surface film formation. The non-linear expression of D-R isotherm can be written as:

$$\left(\frac{x}{m}\right) = q_m \exp[-\beta \cdot \varepsilon^2] \quad \dots \text{Eq.10}$$

Where, x/m represents the amount of adsorbate per unit mass of adsorbent, q_m denotes D–R constant related to the theoretical adsorption capacity ($\text{mol}\ g^{-1}$), β is the constant related to mean free energy of adsorption (mol^2/KJ^2) and ε signifies Polanyi sorption potential which is nothing but the energy required to move 1 mol of any ion from its sorption surface to bulk solution (infinity). The value of ε can be calculated from the following equation (Anirudhan and Suchithra, 2010):

$$\varepsilon = RT \ln \left[1 + \frac{1}{C}\right] \quad \dots \text{Eq.11}$$

where, C is the concentration of P or Zn in equilibrium soil solution. So, the natural logarithmic transformation of the Eq. can be expressed as:

$$\ln \left(\frac{x}{m}\right) = \ln q_m - 2\beta \cdot RT \ln \left[1 + \frac{1}{C}\right] \quad \dots \text{Eq.12}$$

From the β value we can calculate the value of free energy of adsorption (E) ($\text{KJ}\ \text{mol}^{-1}$) which can be defined as the required change in free energy to transfer 1 mol ion from infinity (in bulk solution) to adsorbent surface (Mourabet et al., 2011). It can predict the nature of adsorption whether the adsorption is physisorption or chemisorption. And can be calculated by the following formula:

$$E = \frac{1}{\sqrt{2\beta}} \quad \dots \text{Eq.13}$$

The value of $E < 8$ (KJ mol⁻¹) implies physisorption while $8 < E < 16$ indicates ion exchange phenomena and $E > 16$ (KJ mol⁻¹) denotes chemisorption (Zhou et al., 2024).

Goodness of fit statistics:

In this study, the goodness of fit of the adsorption isotherm models were determined in terms of Determination Coefficient (R^2) (Di Bucchianico, 2008):

$$\text{Coefficient of Determination} = R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2} \quad \dots \text{Eq.14}$$

Here, $\bar{Y}$ represents the mean of the observations, while $\hat{Y}_i$ denotes the predicted value of Y_i based on the fitted model.

Assessment of the thermodynamic properties of the sorption reactions:

The feasibility of the sorption reaction has been assessed from the change in Gibb's free energy (ΔG) (KJ mol⁻¹). The Langmuir constant related to the binding energy (K_L) has been employed to determine the ΔG value through the following equation (Mabuza et al., 2022; Mourabet et al., 2011):

$$\Delta G = RT \ln K_L \quad \dots \text{Eq.15}$$

Here only the positive value or magnitude of K_L have been considered to calculate the ΔG value. So, the Eq.15 can be re-written as:

$$\Delta G = RT \ln |K_L| \quad \dots \text{Eq.16}$$

Statistics and machine learning based predictions:

We used SPSS version 27.0 (SPSS, Inc., Chicago, IL, USA) to carry out the required statistical analyses, and Multiple linear regression-based predictions. R studio (v.4.2.2) was employed to draw violin & box-plot diagrams and correlation matrix. Partial Dependence Plot based visualized predictions also had been employed to evaluate the influence pattern of predictors on targeted variables (R 4.2.2. package "Xgboost" and "Caret"). The graphical representations, regression analysis were created using Microsoft Excel 2019. To assess differences among treatment means, post-hoc test was performed (i.e. Critical Difference and Duncan's Multiple Range Test) at a 5% level of significance using both SPSS version 27.0 and R studio (v.4.2.2).

Results:

Initial Soil characterization:

The soil collected from the experimental site was acidic in reaction (pH_{2.5} 5.38) and non-saline (EC_{2.5} 0.24 dS m⁻¹). The cation exchange capacity, oxidizable organic carbon, and moisture content of the soil was found to be 6.10 cmol (p⁺) kg⁻¹, 0.40%, and 16.50%. The available N, P₂O₅ and K₂O contents of the soil were 146.39 kg ha⁻¹, 19.61 kg ha⁻¹ and 121.17 kg ha⁻¹. The sand, silt and clay content were recorded to be 54.81%, 32.26% and 12.93% suggesting sandy loam texture of the experimental soil. The DTPA-extractable Zn in the soil was found to be 0.96 mg kg⁻¹ suggesting the soils were having low concentration of Zinc (Table 2).

Effect of Zn and P application under different soil moisture regimes on the uptake of P by shoot at 85 days after transplanting (DAT) and 115 DAT:

Single effect of P and Zn:

The single effects of P and Zn on the uptake of P at two different growth stages were depicted in Fig.2a, Fig.2b, Fig.2c and Fig.2d, respectively. With increase in P application rate, the P uptake by shoot had been increased significantly at the both growth stages of rice irrespective of crop cultivars and moisture regimes (Fig.2a & Fig.2b). At 85 DAT, the mean P uptake increased from 16.53 mg plant⁻¹ under P₀ to 19.16 mg plant⁻¹ under P₁ and further to 20.85 mg plant⁻¹ under P₂ (Fig.2a). A similar trend was observed at 115 DAT, where the corresponding values were 25.09, 27.75 and 29.32 mg plant⁻¹, respectively (Fig.2b). The main effect of P was significant as per Fisher's LSD test (LSD value 0.67 and 0.96 respectively for 85 & 115 DAT growth stages at significance level $P < 0.001$) (Table 3). On the other hand, Zn application also significantly influenced P uptake but at the vegetative stage (85 DAT) only (LSD = 0.56 at significance level $P < 0.05$), however the effect was to be non-significant at the reproductive stage (115 DAT). An interesting phenomenon that was observed that instead of showing an antagonistic effect, the uptake of P in shoot was increased with increasing level of Zn application. The mean P uptake by shoot increased from 18.50 mg plant⁻¹ under Zn₀ to 18.88 mg plant⁻¹ under Zn₁ and further to 19.17 mg plant⁻¹ under Zn₂ at 85 DAT (Fig.2c). At 115 DAT, magnitude of the mean P uptake also increased from 27.06 mg plant⁻¹ under Zn₀ to 27.61 mg plant⁻¹ under Zn₂ but the increase is non-significant at all. (Table 3) (Fig.2d). Moreover, from the Duncan's Multiple Range Test (DMRT) it had been confirmed that the overall single effect of graded P and Zn application on P uptake by shoot was significant and non-significant, respectively (Table S.3).

Combine effect of P × Zn:

The combined application of P and Zn (P×Zn) followed the similar trend as that of their single effect. The mean P uptake was highest under the treatment P₂Z₂ for both 85 DAT (21.31 mg plant⁻¹) and 115 DAT (29.77 mg plant⁻¹). Though the individual effect of P and Zn application was significant as per Fischer's LSD test, the P×Zn interaction effect on P uptake was non-significant at all (Table 3).

Effect of V, W and V×W:

The main effects of both variety (V) and water regime (W) on P uptake were equally significant at both the growth stages (LSD = 0.46 and 0.78 respectively for 85 & 115 DAT for both factors at significance level $P < 0.001$). Among the four V×W treatment combinations, IR 64 under continuous flooding (V₂W₁) consistently recorded the highest phosphorus uptake, with mean values of 20.43 mg plant⁻¹ at 85 DAT and 29.24 mg plant⁻¹ at 115 DAT. The lowest uptake was observed under DRR Dhan 45 grown at 50% maximum water holding capacity (V₁W₂), which recorded 17.74 and 25.75 mg plant⁻¹ at 85 and 115 DAT, respectively. However, the interaction effect of V×W was significant at 85 DAT (LSD = 0.64 at $P < 0.05$ level) and non-significant at 115 DAT, suggesting that varietal differences in response to moisture regime diminished as the crop approached maturity (Table 3).

Combine effect of P × Zn × V × W:

Phosphorus uptake by shoot was highest at the treatment P₂Zn₂V₂W₁ for both 85 DAT (22.97 mg plant⁻¹) and 115 DAT (31.78 mg plant⁻¹). The lowest P uptake by shoot was under the treatment P₀Zn₁V₁W₂. (14.42 and 23.31 mg

plant⁻¹ respectively at 85 DAT and 115 DAT). However, the interactions between P × W, Zn × W, P × V, Zn × V, P × Zn × W, P × Zn × V, P × V × W, Zn × V × W, and P × Zn × W × V were non-significant as per Fischer's LSD test (Table 3).

Effect of Zn and P application under different soil moisture regimes on the uptake of Zn by shoot at 85 DAT and 115 DAT:

Single effect of P and Zn:

The single effect of P and Zn on the uptake of Zn at two different growth stages was depicted in Fig.2e, Fig.2f, Fig.2g and Fig.2h, respectively. With increase in P application rate, the Zn uptake by shoot declined significantly at both growth stages of rice irrespective of crop cultivars and moisture regimes (Fig.2e & Fig.2f). At 85 DAT, the mean Zn uptake by shoot decreased from 0.4765 mg plant⁻¹ under P₀ to 0.4645 mg plant⁻¹ under P₁ and further to 0.4553 mg plant⁻¹ under P₂ (Fig.2e). A similar trend was observed at 115 DAT, where the corresponding values were 0.6265, 0.6212 and 0.6086 mg plant⁻¹, respectively (Fig.2f). The main effect of P was significant as per Fisher's LSD test (LSD value 0.0059 for both 85 & 115 DAT stages at significance level P < 0.001) (Table 4). On the other hand, Zn application also significantly influenced Zn uptake by shoot at both growth stages (LSD = 0.0059 for both 85 & 115 DAT at significance level P < 0.05) (Fig.2g and Fig.2h) (Table 4). At 85 DAT, mean Zn uptake increased from 0.3873 mg plant⁻¹ under Zn₀ to 0.4743 mg plant⁻¹ under Zn₁ and further to 0.5347 mg plant⁻¹ under Zn₂ (Fig.2g). At 115 DAT, the mean uptake also increased from 0.5205 mg plant⁻¹ under Zn₀ to 0.6251 mg plant⁻¹ under Zn₁ and further to 0.7126 mg plant⁻¹ under Zn₂ (Fig.2h). From the DMRT result, it was confirmed that the overall single effect of graded Zn application on Zn uptake by shoot was significant but the overall single effect of P application was non-significant (Table S.3). The results indicate that Zn application improved P uptake during the earlier growth stage without exhibiting any antagonistic effect on phosphorus nutrition.

Combine effect of P × Zn:

The combined application of P and Zn (P×Zn) followed the similar trend as that of their single effect. The interaction effect of P × Zn was significant as per Fischer's LSD test at both growth stages (LSD = 0.0103 at significance level P < 0.05 & LSD = 0.0055 at significance level P < 0.001 respectively for 85 & 115 DAT) (Table 4). The mean Zn uptake was highest under the treatment P₀Z₂ for both 85 DAT (0.5555 mg plant⁻¹) and 115 DAT (0.7225 mg plant⁻¹).

Effect of V, W and V×W:

The main effects of both V and W on P uptake were equally significant at both growth stages (LSD = 0.0049 and 0.0026 respectively for 85 & 115 DAT for both factors at significance level P < 0.001). Among the four V×W treatment combinations, DRR Dhan 45 under continuous flooding (V₁W₁) consistently recorded the highest Zn uptake, with mean values of 0.5282 mg plant⁻¹ at 85 DAT and 0.7073 mg plant⁻¹ at 115 DAT. The lowest uptake was observed under IR 64 grown at 50% maximum water holding capacity (V₂W₂), which recorded 0.4518 and 0.5359 mg plant⁻¹ at 85 and 115 DAT, respectively. However, the interaction effect of V×W was non-significant

at 85 DAT but significant (LSD = 0.0036 at $P < 0.001$ level) at 115 DAT, suggesting that varietal differences in response to moisture regime got increased as the crop approached maturity (Table 4).

Combine effect of $P \times Zn \times V \times W$:

Zn uptake by shoot was highest in the treatment $P_0Zn_2V_1W_1$ for both 85 DAT (0.5994 mg plant⁻¹) and 115 DAT (0.7784 mg plant⁻¹). The lowest one was recorded under the treatment $P_2Zn_0V_2W_2$ (0.2945 and 0.4028 mg plant⁻¹ respectively at 85 DAT and 115 DAT). At 85 DAT stage, the interaction between $P \times W$, $Zn \times W$, $P \times Zn \times W$, $P \times V \times W$, $Zn \times V \times W$, $P \times Zn \times W \times V$ were non-significant, whereas the interaction between $P \times V$, $Zn \times V$ and $P \times Zn \times V$ were significant as per Fischer's LSD test. But at 115 DAT stage, the interaction between $P \times W$, $Zn \times W$ and $P \times Zn \times W$ were significant, rest of the interactions exhibited almost the similar trend as those of 85 DAT (Table 4).

Effect of P and Zn application under different soil moisture regimes on the availability of P in soil at 85 DAT and 115 DAT:

Single effect of P and Zn:

The single effect of P and Zn on the availability of P in soil under different soil moisture regimes at two different growth stages was depicted in Fig.3a and Fig.3b. With increase in P application rate, the available P content in soil (kg ha⁻¹) increased significantly at the both growth stages of rice at 85 DAT and 115 DAT for both cultivars and moisture regimes. The availability of P in soil was significantly higher for the dose P_2 compared with P_1 and control (P_0) under each and every rice cultivar and moisture regimes (Fig.3a). At 85 DAT, the mean availability of P increased from 6.51 kg ha⁻¹ under P_0 to 11.54 kg ha⁻¹ under P_1 and further to 16.27 kg ha⁻¹ under P_2 . A similar trend was also recorded at 115 DAT, where the mean P availability in soil increased from 6.21 kg ha⁻¹ (P_0) to 11.13 kg ha⁻¹ (P_1) and further to 15.88 kg ha⁻¹ (P_2). The main effect of P application was significant as per Fisher's LSD test at both 85 DAT (LSD = 0.07 at significance level $P < 0.001$) and 115 DAT (LSD = 0.06 at significance level $P < 0.001$) confirming the positive effect of phosphorus application on P availability in soil (Table 5). On the other hand, an inverse relationship was observed between Zn application and available P content in soil. Significantly the highest availability of P in soil was found under no application of Zn (Zn_0) compared to the doses Zn_1 and Zn_2 at both growth stages of rice (85 DAT and 115 DAT) for both cultivars and moisture regimes (Fig.3b). With increasing levels of Zn, the availability of P decreased significantly in soil and the trend was similar irrespective to variety and soil moisture levels. At 85 DAT, the mean P availability declined from 12.04 kg ha⁻¹ under Zn_0 to 11.36 kg ha⁻¹ under Zn_1 and further to 10.92 kg ha⁻¹ under Zn_2 . Similar reductions were evident at 115 DAT where the mean P availability in soil declined from 11.69 kg ha⁻¹ (Zn_0) to 10.92 kg ha⁻¹ (Zn_1) and further to 10.59 kg ha⁻¹ (Zn_2). The main effect of Zn application was also significant as per Fisher's LSD test at both 85 DAT (LSD = 0.07 at significance level $P < 0.001$) and 115 DAT (LSD = 0.06 at significance level $P < 0.001$), suggesting an antagonistic effect of Zn application on soil P availability (Table 5). From the DMRT result it was confirmed that the overall single effect of graded P & Zn application on the availability of P in soil was significant (Table S.3).

Combine effect of $P \times Zn$:

The combined application of P and Zn ($P \times Zn$) followed the similar trend as that of their single effect. The interaction effect of $P \times Zn$ was significant as per Fischer's LSD test at both growth stages (LSD = 0.13 at significance level $P < 0.001$ & LSD = 0.10 at significance level $P < 0.001$ respectively for 85 & 115 DAT). The highest available soil P was recorded under the treatment P_2Zn_0 with a mean value of 16.95 kg ha⁻¹ at 85 DAT and 16.64 kg ha⁻¹ at 115 DAT. In contrast, the lowest values were observed under P_0Zn_2 (6.14 and 5.89 kg ha⁻¹ at 85 and 115 DAT, respectively) (Table 5).

Effect of V, W and $V \times W$:

The main effects of both V and W on availability of soil P were equally significant at both growth stages (LSD = 0.04 and 0.04 respectively for 85 & 115 DAT for both factors at significance level $P < 0.001$). Among the four $V \times W$ treatment combinations, DRR Dhan 45 under continuous flooding (V_1W_1) consistently recorded the highest availability of P, with mean values of 11.65 kg ha⁻¹ at 85 DAT and 11.31 kg ha⁻¹ at 115 DAT. The lowest availability of P was observed under IR 64 grown at 50% maximum water holding capacity (V_2W_2), which recorded 11.11 and 10.66 kg ha⁻¹ mg plant⁻¹ at 85 and 115 DAT respectively. The interaction effect of $V \times W$ was also significant at both 85 DAT (LSD = 0.04 at $P < 0.001$ level) and 115 DAT (LSD = 0.03 at $P < 0.001$ level) stages (Table 5).

Combine effect of $P \times Zn \times V \times W$:

The combine effect of $P \times Zn \times V \times W$ exhibited significant result on the available P content in soil at both growth stages (LSD = 0.13 & 0.10 at significance level $P < 0.001$ for 85 DAT and 115 DAT respectively). Available P content was highest at the treatment $P_2Zn_0V_1W_1$ for both 85 DAT (17.34 kg ha⁻¹) and 115 DAT (16.98 kg ha⁻¹) stages. The lowest one was recorded under treatment $P_0Zn_2V_2W_2$ (5.78 kg ha⁻¹ and 5.56 kg ha⁻¹ respectively at 85 DAT and 115 DAT). The interaction effect of $P \times W$, $Zn \times W$, $P \times V$, $Zn \times V$, $P \times Zn \times W$, $P \times Zn \times V$, $P \times V \times W$, $Zn \times V \times W$, $P \times Zn \times W \times V$ were significant for both growth stages (Table 5).

Effect of P and Zn application under different soil moisture regimes on the availability of Zn in soil at 85 DAT and 115 DAT:

Single effect of P and Zn:

The single effect of P and Zn on the availability of Zn in soil under different soil moisture regimes at two different growth stages was depicted in Fig.3c and Fig.3d. With increase in P application rate, extractable (available) Zn content in soil (kg ha⁻¹) decreased significantly at both growth stages of rice (85 DAT and 115 DAT) and the trend was similar irrespective to variety and soil moisture levels. The availability of Zn in soil was significantly higher for the dose P_0 (control) compared with P_1 and P_2 for both rice cultivars and moisture regimes (Fig.3c). At 85 DAT, the mean extractable Zn content in soil declined from 7.30 kg ha⁻¹ under P_0 to 6.99 kg ha⁻¹ under P_1 and further to 6.91 kg ha⁻¹ under P_2 . A similar trend was also recorded at 115 DAT, where the mean extractable Zn content in soil declined from 7.13 kg ha⁻¹ (P_0) to 6.84 kg ha⁻¹ (P_1) and further to 6.81 kg ha⁻¹ (P_2). The main effect of P application was significant on availability of Zn in soil as per Fisher's LSD test at both 85 DAT (LSD = 0.05 at significance level $P < 0.001$) and 115 DAT (LSD = 0.06 at significance level $P < 0.001$), suggesting an antagonistic effect of Zn application on soil P availability (Table 6). On the other hand, a substantial increase in extractable Zn content in soil was observed with increasing Zn application doses irrespective to variety and soil

moisture levels. The highest availability of Zn in soil was under the dose Zn_2 than Zn_0 (control) and Zn_1 at both growth stages of rice for both cultivars and moisture regimes (Fig. 3d). At 85 DAT, the mean Zn availability in soil increased from 2.88 kg ha⁻¹ under Zn_0 to 7.76 kg ha⁻¹ under Zn_1 and further to 10.56 kg ha⁻¹ under Zn_2 . A similar trend was also observed at 115 DAT, where mean extractable Zn content increased from 2.75 kg ha⁻¹ (Zn_0) to 7.61 kg ha⁻¹ (Zn_1) and further to 10.42 kg ha⁻¹ (Zn_2). The main effect of Zn application was significant as per Fisher's LSD test at both 85 DAT (LSD = 0.05 at significance level $P < 0.001$) and 115 DAT (LSD = 0.06 at significance level $P < 0.001$), suggesting an antagonistic effect of Zn application on soil P availability (Table 6). From the DMRT result it had been confirmed that the overall single effect of graded P & Zn application on the availability of Zn in soil was significant (Table S.3).

Combine effect of P × Zn:

The combined application of P and Zn ($P \times Zn$) followed the similar trend as that of their single effect. The $P \times Zn$ interaction was significant on the availability of soil Zn at 85 DAT (LSD = 0.03 at significance level $P < 0.001$) and non-significant at 115 DAT. Highest extractable Zn content was recorded under treatment P_0Zn_2 with mean values of 10.82 and 10.60 kg ha⁻¹ at 85 and 115 DAT, respectively. Conversely, the lowest extractable Zn was observed under P_2Zn_0 , with mean values of 2.72 and 2.61 kg ha⁻¹ at 85 and 115 DAT, respectively (Table 6).

Effect of V, W and V×W:

The main effects of both V and W on availability of soil Zn were found to be equally significant at both of the growth stages (LSD = 0.06 and 0.08 respectively for 85 & 115 DAT for both factors at significance level $P < 0.001$). Among the four $V \times W$ treatment combinations, IR 64 under continuous flooding (V_2W_1) consistently recorded the highest availability of Zn with mean values of 7.28 kg ha⁻¹ at 85 DAT and 7.12 kg ha⁻¹ at 115 DAT. The lowest availability of Zn was observed under DRR Dhan 45 grown at 50% maximum water holding capacity (V_1W_2), which recorded 6.85 and 6.74 kg ha⁻¹ mg plant⁻¹ at 85 and 115 DAT respectively. However, the interaction effect of $V \times W$ was non-significant at both growth stages (Table 6).

Combine effect of P × Zn × V × W:

The combined effect of $P \times Zn \times V \times W$ was significant (LSD = 0.01 at significance level $P < 0.05$) on the available Zn content in soil at 85 DAT, but non-significant at 115 DAT. Available Zn content was highest at the treatment $P_0Zn_2V_2W_2$ (10.97 kg ha⁻¹) which was similar to that for treatment $P_0Zn_2V_2W_1$ (10.95 kg ha⁻¹) at 85 DAT. On the other hand at 115 DAT stage, the highest availability of Zn was recorded at the treatment $P_0Zn_2V_2W_1$ (10.77 kg ha⁻¹). The lowest one was recorded under the treatment $P_2Zn_0V_1W_2$ for both 85 DAT (2.49 kg ha⁻¹) and 115 DAT (2.35 kg ha⁻¹). At 85 DAT, the interaction effect of $P \times W$, $Zn \times W$, $P \times V$, $Zn \times V$, $P \times Zn \times W$, $P \times Zn \times V$, $P \times V \times W$ and $Zn \times V \times W$ were significant. However, at 115 DAT, the interaction effect of $P \times W$, $Zn \times W$, $P \times V$, $Zn \times V$, $P \times V \times W$, and $Zn \times V \times W$ were non-significant and those of $P \times Zn \times W$ and $P \times Zn \times V$ were significant.

Estimation of the grain yield of rice under the optimized nutrient and water input from the field study:

Single and Interaction effect of P and Zn:

During the field trial, the single effects of P and Zn were significant ($LSD = 0.14$ for both factors at significance level $P < 0.001$) on rice yield as depicted in Fig. 4. The mean grain yield increased from 50.70 q ha^{-1} under P_0 to 61.75 q ha^{-1} under P_1 and further to 67.08 q ha^{-1} under P_2 (Fig.4A). With respect to the P_0 , the yield increased by 21.8% under P_1 and by 32.3% under P_2 . On the other hand, significantly highest yield was recorded under Zn_0 (54.19 q ha^{-1}) compared to Zn_1 (61.42 q ha^{-1}) and Zn_2 (63.92 q ha^{-1}) (Fig.4B). With respect to Zn_0 , the yield increased by 13.3% and 17.9%, respectively under the treatment Zn_1 and Zn_2 . The interaction effect of $P \times Zn$ followed the similar trend as like the single effects of P and Zn. Among all treatment combinations, the significantly highest grain yield was recorded under P_2Zn_2 (71.75 q ha^{-1}) whereas the lowest one was obtained under P_0Zn_0 (46.07 q ha^{-1}). The interaction effect of $P \times Zn$ was highly significant ($LSD = 0.25$ at the significance level $P < 0.001$) (Table S.4).

Single and Interaction effect of V and W:

The main effects of both V and W on grain yield were equally significant ($LSD = 0.12$ at significance level $P < 0.001$). Significantly the highest grain yield (mean) of rice was produced by the cultivar IR 64 (V_2) (62.67 q ha^{-1}) compared to DRR Dhan 45 (V_1) (57.01 q ha^{-1}). On the other hand, the maximum yield was found under continuous flooding (W_1) (61.57 q ha^{-1}) than 50% maximum water holding capacity (W_2) (58.11 q ha^{-1}), which is 5.9% superior to W_2 . The interaction effect of $V \times W$ followed the similar trend as the single effect of V and W. Among the four $V \times W$ treatment combinations, IR 64 under continuous flooding (V_2W_1) significantly recorded the highest grain yield of rice with a mean value of 64.44 q ha^{-1} . The lowest grain yield was observed under DRR Dhan 45 grown at 50% maximum water holding capacity (V_1W_2) (55.33 q ha^{-1}) (Table S.4).

Interaction effect of P, Zn, V, and W:

The interaction effect of $P \times Zn \times V \times W$ followed the similar trend as the single effect of each of them on grain yield. Grain yield was found to be highest at the treatment $P_2Zn_2V_2W_1$ (78 q ha^{-1}) stages. The lowest one had been recorded under treatment $P_0Zn_0V_1W_2$ (42 q ha^{-1}). The interaction effects of $P \times W$, $Zn \times W$, $P \times V$, $Zn \times V$, $P \times Zn \times W$ and $P \times Zn \times V$ were found to be highly significant ($P < 0.001$) whereas the interaction effects of $P \times V \times W$, $Zn \times V \times W$, and $P \times Zn \times V \times W$ were non-significant (Table S.4).

Effect of water regime and temperature on sorption characteristics of P and Zn in soil system:

To explain the effect of water regime on the availability of P and Zn in soil, a sorption experiment was carried out at two different temperatures 25 and 35°C. The sorption data obtained from the batch experiment was fitted to four adsorption isotherm models as described earlier (Table S.2). At equilibrium, all the sorption parameters of P and Zn obtained from the four isotherm models was summarized in Table 7. It was observed that Dubinin–Radushkevich model gave a better fit to adsorption of P followed by Langmuir, Tempkin and Freundlich models with an average coefficient of determination (R^2) value of 0.98 (Table 7). The model fitting for P sorption followed the order: D-R ($R^2 = 0.98$) > Langmuir ($R^2 = 0.93$) = Tempkin ($R^2 = 0.93$) > Freundlich ($R^2 = 0.86$) at both temperatures, whereas Tempkin model gave the best fit to Zn sorption with an average R^2 value of 0.92. The model fitting for Zn sorption followed the order: Tempkin ($R^2 = 0.92$) > D-R ($R^2 = 0.85$) > Freundlich ($R^2 = 0.77$) > Langmuir ($R^2 = 0.52$) at both temperatures (Fig. 5 & Fig. S1). The Tempkin model at 25°C and 45°C for the

given soils clearly showed that most of the results fitted gentle curves rather than the straight line as required by the theory (Fig.5d). Such behaviour was also reported earlier by Russell et al. (1988) and Roy and De Datta (1985).

Moisture regime dependency of P and Zn sorption:

From the values of the sorption parameters of the best fitted model, the effect of water regime on retention-release pattern of respective nutrients could easily be predicted and explained. From, the D–R (D-R) isotherm of P sorption it could be observed that, free energy of adsorption (E) attained a higher value under W_2 (235.70 and 250 KJ mol⁻¹ at 25°C and 35°C respectively) than that under W_1 (223.60 and 235.7 KJ mol⁻¹ at 25°C and 35°C respectively) for both temperature regimes. The mean free energy of adsorption values were 229.65 and 242.85 KJ mol⁻¹ under W_1 and W_2 , respectively. Moreover, from the Langmuir model the mean of the binding energy of P sorption attained a higher value under W_2 (0.345 L mol⁻¹) than that under W_1 (0.328 L mol⁻¹). Similarly, from the Tempkin isotherm of Zn sorption it was found that maximum binding energy of adsorption (A_T) attained a higher value under W_2 (2.941 and 2.743 L g⁻¹ at 25°C and 35°C respectively) compared with that under W_1 (2.844 and 2.510 L g⁻¹ at 25°C and 35°C respectively) for both temperature regimes. The mean maximum binding energy of adsorption values were 2.68 and 2.84 KJ mol⁻¹ under W_1 and W_2 respectively. Above phenomena together suggest that the release of P and Zn from the exchange complex will be more where the binding energy as well as free energy of sorption will be the less and thus the increased availability of P and Zn under continuous flooded condition (W_1) could be explained mechanistically (Table 7). At both temperatures the values of ΔG (change in Gibb's free energy) were positive for Zn sorption run and negative for P sorption under all treatments implying the non-spontaneous nature of P sorption and spontaneous nature of Zn sorption. The nature of all the sorption reactions were chemisorption due to exhibiting higher E value as interpreted based on D-R model (Table S.5).

Temperature dependency of P and Zn sorption:

Changes in the values of the sorption parameters clearly demonstrated that temperature influenced the sorption behaviour of P and Zn but it affects the process of sorption differently at different moisture levels suggesting a complex interaction between temperature and moisture regime, especially in case of Zn sorption. In case of P sorption, with an increase in temperature from 25°C to 35°C, the magnitude of sorption parameters i.e. (K_F , K_L and q_m values) got increased, suggesting its endothermic nature (Azouzi et al, 2015). The magnitude of the Freundlich coefficient (K_F) increased from 24.14 to 25.69 under W_1 and from 18.71 to 18.96 under W_2 suggesting higher retention of P by the soil at elevated temperature. The magnitude of the adsorption maxima (Q_m) showed only a slight change with increasing temperature, with a range around 12.5–12.8 $\mu\text{g g}^{-1}$ while the magnitude of binding energy (K_L) increased slightly under W_1 (0.324 to 0.332 L mol⁻¹), indicating the effect temperature was more pronounced on sorption kinetics than on the availability of adsorption sites and stronger bonding between P and adsorption sites at elevated temperature. The magnitude of the A_T also increased from 3.560 L g⁻¹ to 3.612 L g⁻¹ under W_1 and from 3.355 L g⁻¹ to 3.368 L g⁻¹ under W_2 with increasing temperature. On the other hand, the magnitude of the E increased from 223.6 to 235.7 KJ mol⁻¹ under W_1 and from 235.7 KJ mol⁻¹ to 250 KJ mol⁻¹ confirming a stronger interaction between P ions and adsorption sites. Unlike P, the effect of temperature on Zn sorption was found highly dependent on soil moisture regime. Under W_1 condition, higher temperature substantially enhanced adsorption parameters, whereas under at 50% of WHC_{max} (W_2) the response was weaker or even negative, demonstrating a complex interaction between temperature and soil moisture, which needs further

study. Zn sorption was found to be more sensitive to changes in soil moisture and temperature regime than P sorption.

Discussion:

In the current study it could be observed that P application substantially increased P uptake and available soil P. Uptake of P increased under higher levels of P application which could be attributed to the enhanced level of P availability in the rhizosphere, leading to more accumulation and uptake by the rice plants. The soil availability and uptake of P are highly correlated ($r = 0.76^{**}$) with each other which already had been confirmed from the correlation analysis of the current study (Fig.6). Enhanced availability of P in soil under enhanced levels of P application could also be observed in Fig.3a. Similar results were also reported by Haque et al. (2025) and He et al. (2006). On the other hand, higher extractable Zn content under higher Zn treated soils may be attributed to the direct addition of Zn to the soil, resulting in greater Zn concentration in the exchangeable and readily extractable pools. Graded application of Zn also had enhanced Zn uptake in plant and the reason might be due to the greater root absorption and efficient translocation. Effectiveness of moving zinc from the roots to the above-ground parts of the plant which depends on four key processes, as outlined by Lasat et al. (1996) and Palmgren et al. (2008), (i) the retention of zinc within the root, (ii) the efficiency of zinc movement through the radial symplastic pathway, (iii) the capacity of the xylem to load zinc, and (iv) the efficiency of zinc movement within the xylem vessels. That's why availability and uptake of Zn was found highly correlated ($r = 0.66^{**}$) with each other (Fig.6).

This study also demonstrated that P and Zn exhibited both synergistic and antagonistic interactions, depending on whether it is in plant or within soil system. It could be observed from the results that P application reduced the availability of Zn in soil and also its uptake in plant, while Zn application slightly reduced availability of soil P but did not reduce its uptake. Actually, the nature of the interaction between P and Zn is governed by their relative availability in the soil and the fertilizer doses applied. Depending on these factors, the interaction may be synergistic, additive, or antagonistic (Srivastava et al., 2014). Antagonism commonly develops when P is applied in excessive amounts compared to Zn, whereas balanced fertilization with both nutrients can result in synergistic or additive effects that enhance plant growth and nutrient utilization (Bayan & Lourdraj, 2000). The reduction in extractable Zn content in soil with increasing phosphorus application may be attributed to P-induced Zn fixation and precipitation reactions, which reduce its solubility and availability in soil suggesting antagonistic effect between them. That's why available P and extractable Zn content in soil were negatively correlated ($r = -0.16$). This phenomenon could also be confirmed from the negative slope value (-0.124) of the regression line drawn between them (Fig.7a). Mandal and Mandal (1990) compared the effect of different P fertilization on transformation of native and applied Zn in a rice-growing soil under flooded and non-flooded regimes in a glasshouse. Application of P not only decreased water-soluble and exchangeable Zn, but concomitantly increased bound forms of soil Zn. These effects were more pronounced under flooded than non-flooded regime. Application of P also showed antagonism with Zn uptake in plant which might be due to the reason that the application of P appeared to lower the translocation of Zn from roots to tops thereby reducing the Zn concentration in shoots. It was also found that, excessive P fertilization leads to Zn deficiency in plant (Norvell et al., 1987; Salimpour et al., 2010). However, graded application of Zn improved P uptake in plant during the earlier growth stage without exhibiting any antagonistic effect which could be ascribed to improved root growth, metabolic activity of root

cells enhancing the nutrient absorption efficiency and uptake (Srivastava et al., 2014). Similar results were also reported by Shivay et al. (2008), Haldar and Mandal et al. (1981). While, at the 115 DAT stage, the main effect of Zn application was non-significant on P uptake. That's why the association between the uptakes of P and Zn was negative ($R^2 = 5.9\%$) (Fig.7b).

On the other hand, flooded conditions (W_1) generally improved nutrient uptake and its availability in soil compared to 50% maximum water-holding capacity (W_2), highlighting the importance of soil water regime in nutrient dynamics. The rise in the concentration of water-soluble phosphorus in acidic soils under submerged conditions is due to several factors. These include: a) The breakdown of iron (III) and aluminium phosphates through hydrolysis. b) The liberation of phosphorus that was previously held through anion exchange on clay and the hydrous oxides of iron (III) and aluminium. c) The reduction of iron (III) to iron (II), which leads to the release of phosphorus that was sorbed and chemically bonded (Ponnamperuma, 1972). Continuous flooding generally favoured greater phosphorus uptake compared with the moisture-stress condition (W_2), likely due to improved nutrient diffusion and greater P availability under reduced soil conditions. The decreased P availability with loss of soil-water saturation may be due to greater phosphate sorption capacity of the soils during flooding and after re-oxidation due to occlusion of P within ferric oxyhydroxides formed, which was also confirmed from the sorption study as discussed in the section 3.7.2 (Table 7). The highest root porosity observed in plants cultivated under continuous flooding conditions. This increased root porosity is connected to greater root length, increased dry mass of both roots and shoots, and a higher concentration of nutrients in the shoot tissues (Das and Jat, 1977). Hence the phosphorus uptake was higher in continuous flooding. It was also observed that the availability zinc was always higher in case of W_1 in respect to W_2 which could be attributed to increased formation of Fe^{2+} and Mn^{2+} resulting from the reduction of their higher valent oxides. These elements compete with Zn^{2+} for spots on the exchange sites, limiting the binding of applied Zn into this exchange system. This phenomenon was also confirmed from the sorption study as discussed in the section 3.7.2. The greater amounts of soluble Fe^{2+} and Mn^{2+} might also replace some of the Zn that already bound to the exchange sites, causing it to interact with P in the liquid phase and creating less soluble compounds (Mandal and Mandal, 1990). These results align with the findings reported by Mandal and Mandal (1988). Same findings were also supported by Naik and Das (2007).

The superior yield performance exhibited by the cultivar IR 64 (V_2) under the treatment $P_2Zn_2W_1$ may be attributed to its better phosphorus uptake, utilization and improved sink capacity than DRR Dhan 45 (V_2). Higher level of P applied under continuous flooded condition enhanced P availability and uptake with better root development, tillering and photosynthetic activity and thus increased dry matter production and assimilate partition improving the yield. The crucial role of P on the yield performance of rice was further explained via several model-based approaches.

Approaches had been employed in this study to predict the yield performance of the cultivar under field condition based on the data collected from the pot experiment maintaining the similar treatment combinations. Firstly, Pearson correlation study was carried out to find the relationship between field (i.e. grain yield) and pot data (i.e. nutrient uptakes and their availability in soil) where it was found that grain yield of rice was highly correlated with P uptake and P availability in soil. The correlation between grain yield and nutrient uptakes and availability followed the pattern: P uptake by shoot ($r = 0.86^{***}$) > available P in soil ($r = 0.69^{***}$) > extractable Zn in soil

($r = 0.44^{***}$) >> Zn uptake by shoot (0.042) (Fig.6). Multiple regression modelling (linear) had also been performed to predict nutrient–response relationships. It was observed that variations in grain yield of rice under field condition could be explained 91.60% together by the variations in P uptake, Zn uptake, available P content and extractable Zn content in soil, wherein the variation in P uptake alone contributed to 72.80% variation in the response (Table 8). Additionally, simple regression analysis (linear) was also conferred to assess the variation contributed by a single factor to the variation of response. Variations in grain yield 82.45% explained by the variation in the uptake of P by shoot (Fig.7c) but at the same time variations in the uptake of Zn by shoot failed to explain any variation in the same response (Fig.7d). The partial dependence plot (PDP), displaying the partial influence of both P and Zn uptake on grain yield are given in Fig. 8. The heatmap revealed a distinct colour gradient along the horizontal axis (P uptake), whereas comparatively smaller changes occur along the vertical axis (Zn uptake) which indicated that predicted grain yield was more sensitive to variations in P uptake than to Zn uptake, whereas the interaction between P and Zn was much weaker corroborating the results obtained from regression analysis.

Results from the sorption study suggests that the sorption process may be diffusion controlled. As diffusion is strictly a temperature dependent process, it can also be explained by Arrhenius type of equation (Eq.17) (Barrow 1986; Lee et al., 1998, Jain et al., 2004; Chen et al., 2015). The temperatures 25°C and 35°C were selected because they represent realistic thermal conditions in soil generally experienced in tropical and subtropical regions. A temperature of 25°C is widely adopted as the reference temperature in sorption-desorption, kinetics and thermodynamic studies and approximates the average soil temperature during the rice-growing season. The higher temperature (35°C) simulates elevated soil temperatures commonly observed during peak summer months in paddy fields. The 10°C temperature interval is sufficiently large to detect measurable changes in the thermodynamic nature of sorption or desorption reaction. On treating an acid soil with a P solution, P tends to get adsorbed, causing a fall in its concentration in the solution immediately adjacent to the surface. This creates a concentration gradient across the thin film of solution surrounding the soil particles, and hence, diffusion of P occurred from the bulk solution to the surface of the particles across the thin films (Sanyal et al., 1993). Moreover, temperature increased the molecular mobility facilitating diffusion of P toward reactive Fe and Al-oxide and Zn towards Fe and Mn oxides surfaces promoting a stronger surface complexation for chemisorption, especially under W_1 condition. However, under W_2 , the sorption of Zn got decreased, likely because reduced soil moisture limited the diffusion pathways and altered surface charge characteristics, thereby decreasing Zn retention.

$$D = D_0 \cdot \exp\left[-\frac{Q_0}{RT}\right] \quad \text{..... Eq.17}$$

Where,

D - Diffusion Coefficient

D_0 - Pre exponential constant

Q_0 - Energy of Activation

R - Universal Gas Constant

T - Absolute temperature

Conclusion

The results demonstrated that predicted grain yield was primarily driven by P nutrition, while adequate Zn supply enhanced its beneficial effects only. Although weak negative relationships between P and Zn uptake and between available P and Zn suggested slight P-induced Zn antagonism, the effect was negligible and did not reduce the grain yield. Instead, balanced P and Zn fertilization acted in a complementary rather than a strongly antagonistic manner and prevented Zn deficiency. Once sufficient Zn uptake was achieved, additional Zn contributed little to yield improvement, highlighting the importance of maintaining adequate rather than excessive Zn supply. Overall, P management should be the primary focus, supported by adequate Zn nutrition. $P_2Zn_2V_2W_1$ produced the highest grain yield through balanced nutrient supply, making it the optimum treatment combination. Additionally, the findings from the sorption study implied that increase in temperature in rice soils may increase nutrient retention, particularly under continuous flooding, although the response of Zn is more sensitive to soil moisture regime.

Acknowledgements:

The authours are greatful to the Department of Soil Science and Agricultural Chemistry, and RKVY soil testing laboratory, UBKV, Pundibari for the analytical support.

Author contributions:

Tathagata Karmakar: Writing-Original draft preparation, Investigation

Rohit Kumar Choudhury: Writing-Original draft preparation, Reviewing and Editing, Formal analysis, Data curation, Visualization, Mathematical calculations, Software

Dibyendu Mukhopadhyay: Conceptualization, Methodology, Investigation, Supervision, Reviewing, and Validation

Sumana Balo: Reviewing and Editing

Sayan Debsingha: Investigation

Ganesh Chandra Banik: Reviewing, Data curation and Validation

Ranjan Bhattacharyya: Reviewing, Validation

Funding: The necessary funding was provided by Uttar Banga Krishi Viswavidyalaya (UBKV), Pundibari, Cooch Behar, West Bengal, India for this research.

Conflict of Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability:

Data will be available on request

661 **References:**

- 662 Abdullah, A. S. (2015). Zinc availability and dynamics in the transition from flooded to aerobic rice
663 cultivation. *Journal of Plant Biology & Soil Health*, 2(1), 2-5.
- 664 Abuzaid, A. S., & Bassouny, M. A. (2020). Total and DTPA-extractable forms of potentially toxic metals in soils
665 of rice fields, north Nile Delta of Egypt. *Environmental Technology & Innovation*, 18, 100717.
666 <https://doi.org/10.1016/j.eti.2020.100717>
- 667 Alloway, B. J. (2009) Soils factors associated with zinc deficiency in crops and humans. *Environmental*
668 *Geochemistry and Health*, 31(5): 537–548. <https://doi.org/10.1007/s10653-009-9255-4>
- 669 Al-Wahbi, A. A. M., & Dammag, H. A. Q. (2011). Removal of methylene blue from aqueous solutions using
670 Yemen bentonite. *Diyala Journal of Engineering Sciences*, 04(01):30-53
- 671 Anirudhan, T. S., & Suchithra, P. S. (2010). Heavy metals uptake from aqueous solutions and industrial
672 wastewaters by humic acid-immobilized polymer/bentonite composite: kinetics and equilibrium
673 modeling. *Chemical Engineering Journal*, 156(1), 146-156. <https://doi.org/10.1016/j.ccej.2009.10.011>.
- 674 AOAC. (1970). Official Methods of Analysis. 11th ed. Association of Official Analytical Chemists. Washington,
675 D.C.
- 676 Atugoda, T., Gunawardane, C., Ahmad, M., & Vithanage, M. (2021). Mechanistic interaction of ciprofloxacin on
677 zeolite modified seaweed (*Sargassum crassifolium*) derived biochar: Kinetics, isotherm and
678 thermodynamics. *Chemosphere*, 281, 130676. <https://doi.org/10.1016/j.chemosphere.2021.130676>
- 679 Azouzi, R., Charef, A., & Hamzaoui, A. H. (2015). Assessment of effect of pH, temperature and organic matter
680 on zinc mobility in a hydromorphic soil. *Environmental Earth Sciences*, 74, 2967–2980.
681 <https://doi.org/10.1007/s12665-015-4328-4>.
- 682 Barrow, N. J. (1986). Testing a mechanistic model II: The effects of time and temperature on the reaction of zinc
683 with a soil. *Soil Science*, 37, 277–286. <https://doi.org/10.1111/j.1365-2389.1986.tb00029.x>
- 684 Barrow, N. J. (1984) Modelling the effects of pH on sorption by soils. *Advances of Agronomy*, 38, 183-230
- 685 Bayan, H. C., & Lourduraj, A. C. (2000). Phosphorus management in rice and rice based cropping systems—A
686 review. *Agricultural Reviews*, 21(2), 89-96.
- 687 Black, C. A., Evans, D. D., Ensminger, L. E., White, J. L., & Clark, F. E. (Eds.). (1965). *Methods of soil analysis.*
688 *Part 1: Physical and mineralogical properties, including statistics of measurement and sampling.* American
689 Society of Agronomy.
- 690 Bouyoucos, G. J. (1962) Hydrometer method improved for making particle-size analysis of soils. *Agronomy*
691 *Journal*, 54: 464-65. <https://doi.org/10.2134/agronj1962.00021962005400050028x>.
- 692 Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil*
693 *science*, 59(1), 39-46.
- 694 Chen, X. (2015). Modeling of experimental adsorption isotherm data. *information*, 6(1), 14-22.
- 695 Chen, H. L., Ju, S. P., Wu, T. Y., Hsieh, J. Y., & Liu, S. H. (2015). Investigation of Zr and Si diffusion behaviors
696 during reactive diffusion—a molecular dynamics study. *RSC Advances*, 5(33), 26316–26320.
697 <https://doi.org/10.1039/C4RA16962J>.

- 699 Cheung, K. C., & Venkitachalam, T. H. (2006). Kinetic studies on phosphorus sorption by selected soil
700 amendments for septic tank effluent renovation: KC Cheung and TH Venkitachalam. *Environmental*
701 *Geochemistry and Health*, 28(1), 121-131. <https://doi.org/10.1007/s10653-005-9021-1>
- 702 Chien, S. H., & Clayton, W. R. (1980). Application of Elovich equation to the kinetics of phosphate release and
703 sorption in soils. *Soil Science Society of America Journal*, 44, 265–268.
704 <https://doi.org/10.2136/sssaj1980.03615995004400020013x>.
- 705 Dada, A. O., Olalekan, A. P., Olatunya, A. M., & Dada, O. J. I. J. C. (2012). Langmuir, Freundlich, Temkin and
706 Dubinin–Radushkevich isotherm studies of equilibrium sorption of Zn^{2+} unto phosphoric acid-modified rice
707 husk. *Iosr J. Appl. Chem*, 3(1), 38-45.
- 708 Das D K and Jat R L (1977) Influence of Three Soil-water Regimes on Root Porosity and Growth of Four Rice
709 Varieties 1. *Agronomy Journal*, 69(2): 197-200. <https://doi.org/10.2134/agronj1977.00021962006900020001x>
- 710 de la Rosa, G., Reynel-Avila, H. E., Bonilla-Petriciolet, A., Cano-Rodríguez, I., Velasco-Santos, C., & Martínez-
711 Hernández, A. L. (2008). Recycling poultry feathers for Pb removal from wastewater: kinetic and equilibrium
712 studies. *International Journal of Chemical and Biomolecular Engineering*, 1(4), 185-193.
- 713 Dewis J and Freitas F (1984) In Physical and Chemical Methods of Soil and Water Analysis. *Food and*
714 *Agricultural Organization soils bulletin* 10: 1-275.
- 715 Di Bucchianico, A. (2008). Coefficient of determination (R^2). In *Encyclopedia of Statistics in Quality and*
716 *Reliability*. <https://doi.org/10.1002/9781118445112.stat03980>
- 717 Dotaniya, M. L., & Meena, V. D. (2015). Rhizosphere effect on nutrient availability in soil and its uptake by
718 plants: a review. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, 85(1),
719 1-12. <https://doi.org/10.1007/s40011-013-0297-0>
- 720 Fatehi Falahati, H., Khalilirad, M., Forghani, A., & Fazeli Sangani, M. (2021). The Effect of Waterlogging
721 on Distribution of Different Forms of Zinc in Acidic and Alkaline Soils. *Iranian Journal of Soil and Water*
722 *Research*, 52(6), 1491-1500. <https://doi.org/10.22059/ijswr.2021.315931.668847>.
- 723 Freundlich, H. (1926) *Colloid and Capillary Chemistry*. Methuen, London.
- 724 Ganeshamurthy, A. N., Kalaivanan, D., & Satisha, G. C. (2016). Management of vegetable crops in acid soils of
725 India. *Innovations in Horticultural Sciences*, 559-584.
- 726 Gao, X., Hoffland, E., Stomph, T., Grant, C. A., Zou, C., & Zhang, F. (2012). Improving zinc bioavailability
727 in transition from flooded to aerobic rice. A review. *Agronomy for sustainable development*, 32(2), 465-478.
728 <https://doi.org/10.1007/s13593-011-0053-x>
- 729 Godebo, T., Laekemariam, F., & Loha, G. (2021). Nutrient uptake, use efficiency and productivity of bread wheat
730 (*Triticum aestivum* L.) as affected by nitrogen and potassium fertilizer in Keddida Gamela Woreda, Southern
731 Ethiopia. *Environmental Systems Research*, 10(1), 12. <https://doi.org/10.1186/s40068-020-00210-4>

732 González-Paz, J. R., del Carmen Monterrubio-Badillo, M., Ordaz, A., García-Peña, E. I., & Guerrero-
733 Barajas, C. (2022). Influence of Fe²⁺ and Fe³⁺ on the Performance and Microbial Community Composition of a
734 MFC Inoculated with Sulfate-Reducing Sludge and Acetate as Electron Donor. *Journal of Chemistry*, 2022(1),
735 5685178. <https://doi.org/10.1155/2022/5685178>

736 Günay, A., Arslankaya, E., & Tosun, I. (2007). Lead removal from aqueous solution by natural and pretreated
737 clinoptilolite: adsorption equilibrium and kinetics. *Journal of hazardous materials*, 146(1-2), 362-371.
738 <https://doi.org/10.1016/j.jhazmat.2006.12.034>

739 Habte, D., Kebede, F., Bedadi, B., & Wogi, L. (2020). Phosphorus sorption–desorption properties of Luvisols and
740 Vertisols, sorption kinetics and models comparison. *Communications in Soil Science and Plant Analysis*, 51(4),
741 527-540. <https://doi.org/10.1080/00103624.2020.1717512>.

742 Halder, M. & Mandal L N (1981) Effect of phosphorus and zinc on the growth and phosphorus, zinc, copper, iron
743 and manganese nutrition of rice. *Plant and Soil*, 59(3): 415-425. <https://doi.org/10.1007/BF02184546>.

744 Haque, M. A., Jahiruddin, M., & Bell, R. W. (2025). Early sowing of wheat with minimum tillage on wet soils
745 increases yield potential and phosphorus fertilizer requirements on the coastal ecosystem. *Journal of soil science*
746 *and plant nutrition*, 25(1), 1047-1058. <https://doi.org/10.1007/s42729-024-02183-0>.

747 Hayward, D., & Trapnell, B. (1964). Chemisorption. London: Butterworth.

748 He, Z., Griffin, T. S., & Honeycutt, C. W. (2006). Soil phosphorus dynamics in response to dairy manure and
749 inorganic fertilizer applications. *Soil science*, 171(8), 598-609. DOI: 10.1097/01.ss.0000228039.65023.20

750 Huang, L., Fu, L., Jin, C., Gielen, G., Lin, X., Wang, H., & Zhang, Y. (2011). Effect of temperature on
751 phosphorus sorption to sediments from shallow eutrophic lakes. *Ecological Engineering*, 37(10), 1515-1522.
752 <https://doi.org/10.1016/j.ecoleng.2011.05.006>

753 Jackson, M. L. (1967). Soil chemical analysis. Prentice Hall of India.

754 Jackson, M.L., 1973, Soil Chemical Analysis, Prentice Hall, New Delhi.

755 Jain, R. (2023). Determination of soil textural class by using USDA soil texture triangle. *International Journal of*
756 *Innovative Research and Growth*, 12(3), 56-61.

757 Jain, C. K., Singhal, D. C., & Sharma, M. K. (2004). Adsorption of zinc on bed sediment of River Hindon:
758 Adsorption models and kinetics. *Journal of Hazardous Materials*, 114, 231–239.
759 <https://doi.org/10.1016/j.jhazmat.2004.09.001>.

760 Jodeh, S., Odeh, R., Sawalha, M., Obeid, A. A., Salghi, R., Hammouti, B., Radi, S., & Warad, I. (2015). Adsorption
761 of lead and zinc from used lubricant oil using agricultural soil: equilibrium, kinetic and thermodynamic studies. *J.*
762 *Mater. Environ. Sci*, 6(2), 580-591.

763 Johnston, B. R., Duncan, C. W., Lawton, K., & Benne, E. J. (1952). Determination of potassium in plant materials
764 with a flame photometer. *J. Ass. Offic. Agr. Chem*, 35, 813.

765 Kuo, S. and Lotse, E. G. (1974). Kinetics of phosphate adsorption and desorption by lake sediments. *Soil Science*
766 *Society of America Journal*, 38(1): 50-54. <https://doi.org/10.2136/sssaj1974.03615995003800010021x>.

767 Langmuir, I. (1918) The Adsorption of Gases on Plane Surface of Glass, Mica and Olatinum. *Journal of the*
768 *American Chemical Society*, 40, 1361-1403. <http://dx.doi.org/10.1021/ja02242a004>.

769 Lasat, M. M., Baker, A. J. M., Kochian, L. V. (1996) Physiological characterization of root Zn^{2+} absorption and
 770 translocation to shoots in Zn hyperaccumulator and nonaccumulator species of *Thlaspi*. *Plant Physiology*,
 771 **112**(4),1715-1722. <https://doi.org/10.1104/pp.112.4.1715>
 772 Lee, S. H., Vigneswaran, S., & Moon, H. (1998). Phosphorus removal using steel industry byproducts under static
 773 system. *Indian Chemical Engineer A*, *40*, 1–6.
 774 Lindsay, W. L., & Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper.
 775 *Soil science society of America journal*, *42*(3), 421-428.
 776 Mabuza, M., Premllal, K., & Daramola, M. O. (2022). Modelling and thermodynamic properties of pure CO₂ and
 777 flue gas sorption data on South African coals using Langmuir, Freundlich, Temkin, and extended Langmuir
 778 isotherm models. *International Journal of Coal Science & Technology*, *9*(1), 45. [https://doi.org/10.1007/s40789-](https://doi.org/10.1007/s40789-022-00515-y)
 779 [022-00515-y](https://doi.org/10.1007/s40789-022-00515-y)
 780 Maclean, J.C., Dawe, D.C., Hardy, B. and Hettel, G.P. (2002). Rice almanac (3rd edition)CABI publishing
 781 willing ford, p. 253.
 782 Mandal, B., & Mandal, L. N. (1990). Effect of phosphorus application on transformation of zinc fraction in soil
 783 and on the zinc nutrition of lowland rice. *Plant and Soil*, *121*(1), 115-123. <https://doi.org/10.1007/BF00013104>
 784 Mandal, B., Hazra, G. C. & Pal, A. K. (1988) Transformation of zinc in soils under submerged condition and its
 785 relation with zinc nutrition of rice. *Plant and soil*, *106*: 121-126. <https://doi.org/10.1007/BF02371203>
 786 Mandal, L. N., & Mandal, B. (1987). Transformation of zinc fractions in rice soils. *Soil science*, *143*(3), 205-212.
 787 Mourabet, M., El Boujaady, H., El Rhilassi, A., Ramdane, H., Bennani-Ziatni, M., El Hamri, R., & Taitai, A.
 788 (2011). Defluoridation of water using Brushite: Equilibrium, kinetic and thermodynamic
 789 studies. *Desalination*, *278*(1-3), 1-9.<https://doi.org/10.1016/j.desal.2011.05.068>.
 790 Sarkar, P., Ray, P. R., Ghatak, P. K., & Sen, M. (2016). Arsenic concentration in water, rice straw and cow milk–
 791 a micro level study at Chakdaha and Haringhata block of West Bengal. *Indian J Dairy Sci*, *69*(6), 676-679.
 792 Nelson, D. W., & Sommers, L. E. (1982). Total carbon, organic carbon, and organic matter. *Methods of soil*
 793 *analysis: Part 2 chemical and microbiological properties*, *9*, 539-579.
 794 <https://doi.org/10.2134/agronmonogr9.2.2ed.c29>.
 795 Norvell, W. A., Dabkowska-Naskret, H., & Cary, E. E. (1987). Effect of phosphorus and zinc fertilization on the
 796 solubility of Zn^{2+} in two alkaline soils. *Soil Science Society of America Journal*, *51*(3), 584-588.
 797 <https://doi.org/10.2136/sssaj1987.03615995005100030006x>
 798 Palmgren, M. G., Clemens, S., Williams, L. E., Krämer, U., Borg, S., Schjørring, J. K., & Sanders, D. (2008).
 799 Zinc biofortification of cereals: problems and solutions. *Trends in plant science*, *13*(9), 464-473.
 800 Pati, R., & Mukhopadhyay, D. (2016). Arsenic sorption/desorption kinetics in some soils of West Bengal. *Journal*
 801 *of Agriculture and Technology*, *3*(2), 19.
 802 Ponnampetuma, F. N. (1972). The chemistry of submerged soils. *Advances in agronomy*, *24*, 29-96.
 803 [https://doi.org/10.1016/S0065-2113\(08\)60633-1](https://doi.org/10.1016/S0065-2113(08)60633-1).
 804 Reynolds, S. G. (1970). The gravimetric method of soil moisture determination Part IA study of equipment, and
 805 methodological problems. *Journal of Hydrology*, *11*(3), 258-273.

806 Roy, A. C., & De Datta, S. K. (1985). Phosphate sorption isotherms for evaluating phosphorus requirement of
807 wetland rice soils. *Plant and soil*, 86(2), 185-196. <https://doi.org/10.1007/BF02182893>

808 Russell, J. S., Kamprath, E. J., & Andrew, C. S. (1988). Phosphorus sorption of subtropical acid soils as influenced
809 by the nature of the cation suite. *Soil Science Society of America Journal*, 52(5), 1407-1410.
810 <https://doi.org/10.2136/sssaj1988.03615995005200050038x>.

811 Saleh, Tawfik A. "Isotherm models of adsorption processes on adsorbents and nanoadsorbents." *Interface science
812 and technology*. Vol. 34. Elsevier, 2022. 99-126.

813 Salimpour, S. I., Khavazi, K., Nadian, H., Besharati, H., & Miransari, M. (2010). Enhancing phosphorous
814 availability to canola ('Brassica napus' L.) using P solubilizing and sulfur oxidizing bacteria. *Australian Journal
815 of Crop Science*, 4(5), 330-334.

816 Sanyal, S. K. (2018). *A textbook of soil chemistry*. Daya Publishing House.

817 Sanyal, S. K., & De Datta, S. K. (1991). Chemistry of phosphorus transformations in soil. In *Advances in soil
818 science: volume 16* (pp. 1-120). New York, NY: Springer New York.

819 Sanyal, S. K., & De Datta, S. K. (1991). Chemistry of phosphorus transformations in soil. In *Advances in
820 soil science: volume 16* (pp. 1-120). New York, NY: Springer New York.
821 <https://doi.org/10.2136/sssaj1993.03615995005700040011x>

822 Sanyal, S. K., Chan, P. Y., & De Datta, S. K. (1993). Phosphate sorption-desorption behavior of some acidic soils
823 of south and southeast Asia. *Soil Science Society of America Journal*, 57(4), 937-945.
824 <https://doi.org/10.2136/sssaj1993.03615995005700040011x>

825 Shivay, Y. S., Kumar, D., Prasad, R., & Ahlawat, I. P. S. (2008). Relative yield and zinc uptake by rice from zinc
826 sulphate and zinc oxide coatings onto urea. *Nutrient Cycling in Agroecosystems*, 80(2), 181-188.
827 <https://doi.org/10.1007/s10705-007-9131-5>.

828 Shuman, L. M., & Duncan, R. R. (1990). Soil exchangeable cations and aluminum measured by ammonium
829 chloride, potassium chloride, and ammonium acetate. *Communications in Soil Science and Plant Analysis*, 21(13-
830 16), 1217-1228.

831 Singh, V. K., & Kumar, E. A. (2018). Comparative studies on CO₂ adsorption isotherms by solid
832 adsorbents. *Materials Today: Proceedings*, 5(11), 23033-23042. <https://doi.org/10.1016/j.matpr.2018.11.032>

833 Singh, V., Singh, V., Singh, S., & Khanna, R. (2020). Effect of zinc and silicon on growth and yield of aromatic
834 rice (*Oryza Sativa*) in north-western plains of India. *J. Rice Res. Dev*, 3(1), 82-86.
835 <https://doi.org/10.36959/973/424>.

836 Sparks DL, Page AL, Helmke PA, Leoppert RH, Soltanpour PN, Tabatabai MA, Johnston CT, and Sumner ME
837 (2006). Methods of soil analysis. Part 3. *Chemical methods*. Madison, *Soil Science Society of America*, 811–831.

838 Sposito, G. (1980). Derivation of the Freundlich equation for ion exchange reactions in soils. *Soil Science Society
839 of America Journal*, 44(3), 652-654. <https://doi.org/10.2136/sssaj1980.03615995004400030045x>

840 Srivastava, P. C., Bhatt, M., Pachauri, S. P., & Tyagi, A. K. (2014). Effect of zinc application methods on apparent
841 utilization efficiency of zinc and phosphorus fertilizers under basmati rice–wheat rotation. *Archives of Agronomy
842 and Soil Science*, 60(1), 33-48. <https://doi.org/10.1080/03650340.2013.770145>.

843 Subbiah, B.V. and Ashija, G.L. (1956) A rapid procedure for the determination of available nitrogen in soils.
844 *Current Sciences*, 25,259-260.

- Vodyanitskii, Y. N. (2010). Zinc forms in soils (Review of publications). *Eurasian Soil Science*, 43(3), 269-277. <https://doi.org/10.1134/S106422931003004X>.
- Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil science*, 37(1), 29-38.
- Warncke, D., & Brown, J. R. (1998). Potassium and other basic cations. *Recommended chemical soil test procedures for the North Central Region*, 1001, 31.
- Wasewar, K. L., Atif, M., Prasad, B., & Mishra, I. M. (2008). Adsorption of zinc using tea factory waste: kinetics, equilibrium and thermodynamics. *CLEAN–Soil, Air, Water*, 36(3), 320-329. <https://doi.org/10.1002/clen.200700139>.
- Xie, F., Dai, Z., Zhu, Y., Li, G., Li, H., He, Z., Geng S. & Wu, F. (2019). Adsorption of phosphate by sediments in a eutrophic lake: Isotherms, kinetics, thermodynamics and the influence of dissolved organic matter. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 562, 16-25. <https://doi.org/10.1016/j.colsurfa.2018.11.009>.
- Zhao, K., & Selim, H. M. (2010). Adsorption–desorption kinetics of Zn in soils: Influence of phosphate. *Soil Science*, 175(4), 145–153. <https://doi.org/10.1097/SS.0b013e3181dd51a0>
- Zhou, B., Li, H., Wang, Z., Huang, H., Wang, Y., Yang, R.,Huo,R.,Xu,X., Zhou,T& Dong, X. (2024). Prediction of phosphate adsorption amount, capacity and kinetics via machine learning: A generally physical-based process and proposed strategy of using descriptive text messages to enrich datasets. *Chemical Engineering Journal*, 479, 147503. <https://doi.org/10.1016/j.cej.2023.147503>
- Zhou, D., Liu, D., Gao, F., Li, M., & Luo, X. (2017). Effects of biochar-derived sewage sludge on heavy metal adsorption and immobilization in soils. *International Journal of Environmental Research and Public Health*, 14, 681. <https://doi.org/10.3390/ijerph14070681>.

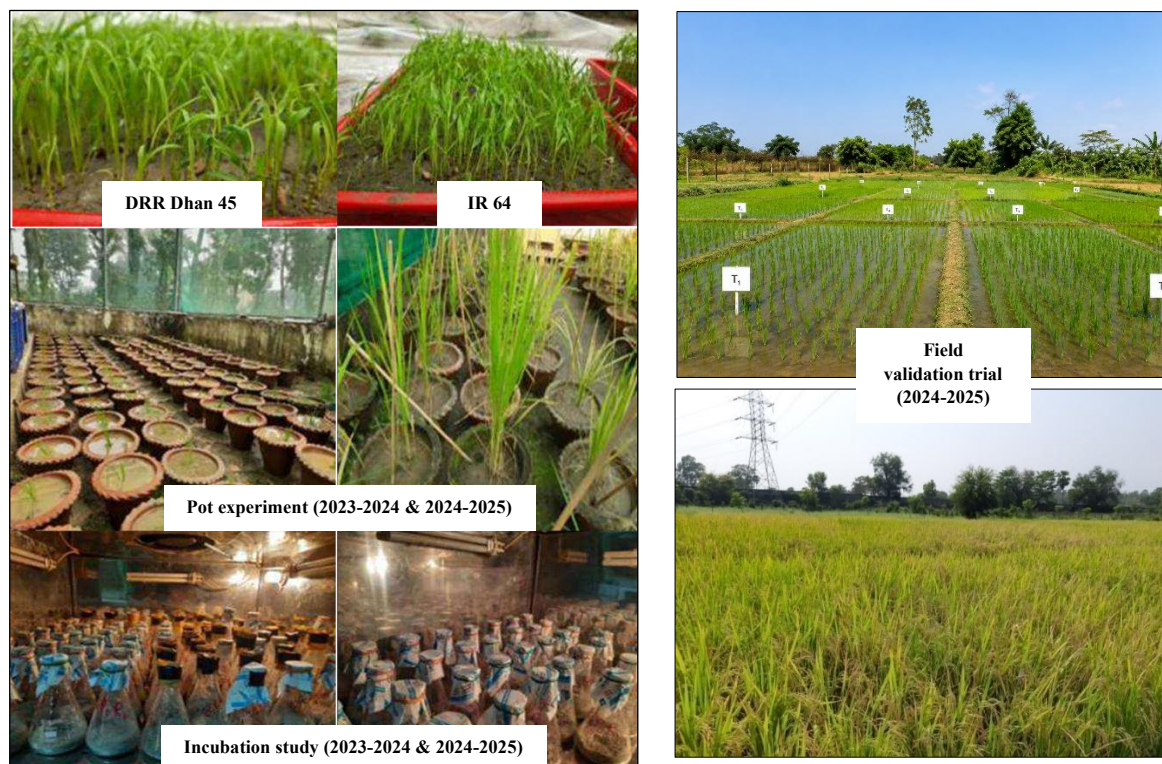
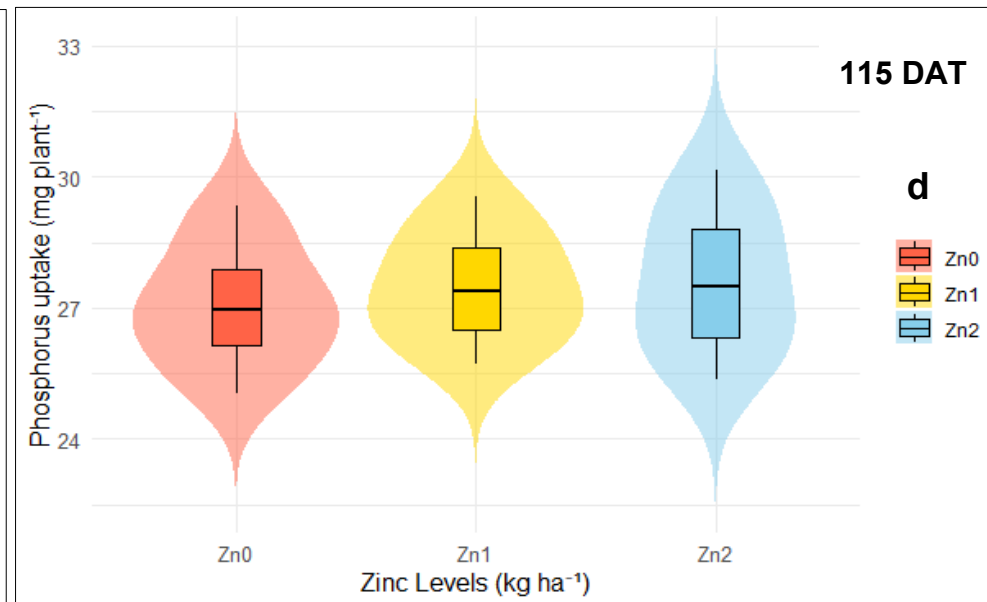
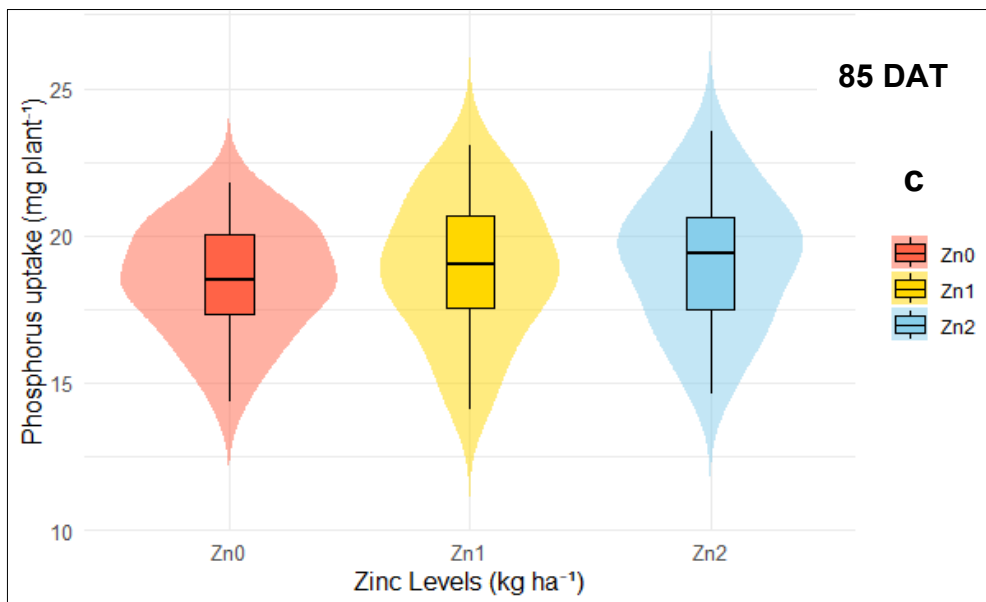
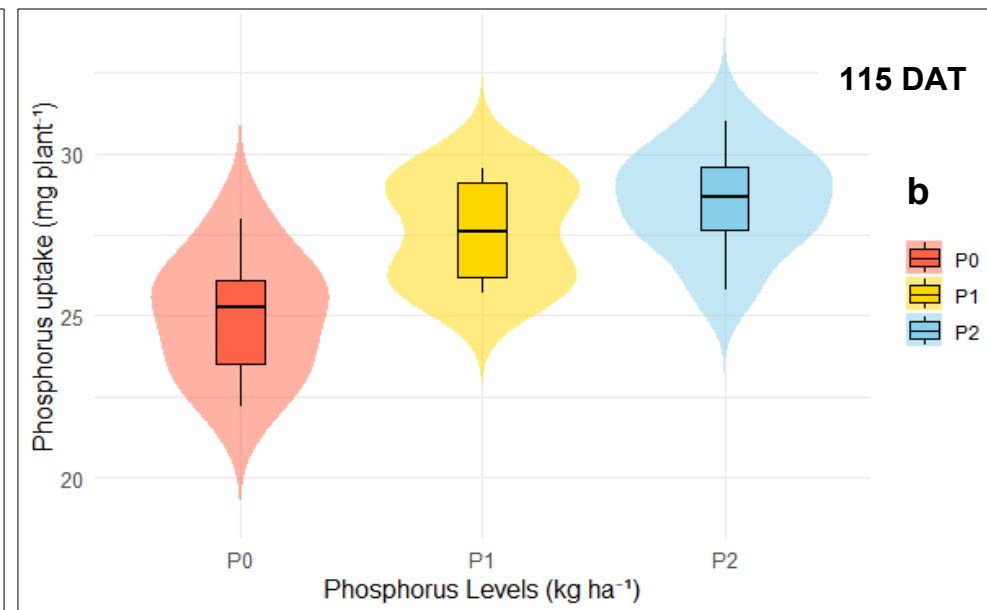
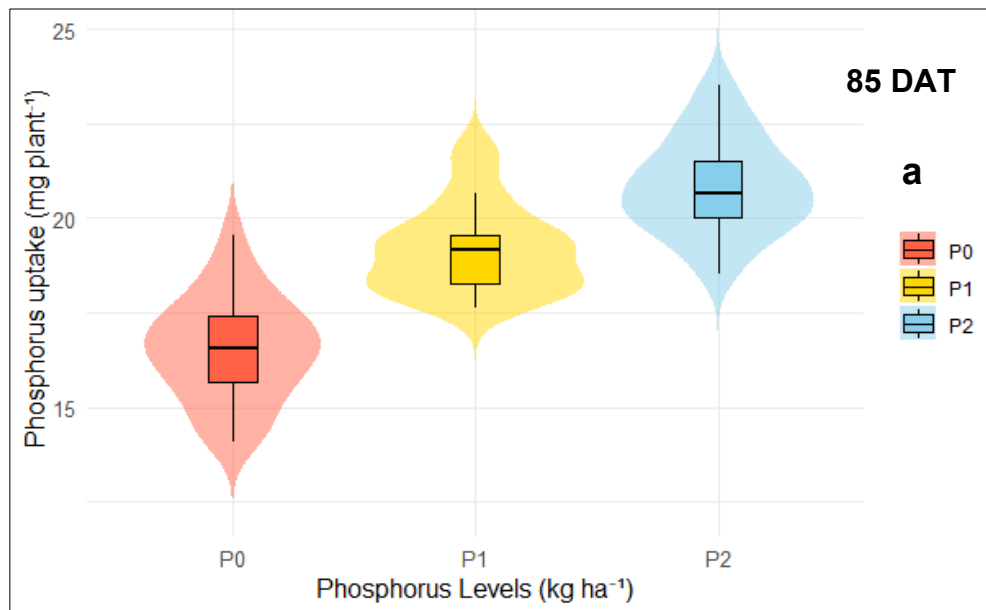


Fig.1. Pot experiment, incubation study and field trial conducted under Uttar Banga Krishi Viswavidyalaya, Cooch Behar, India for two consecutive years 2023-2024 & 2024-2025



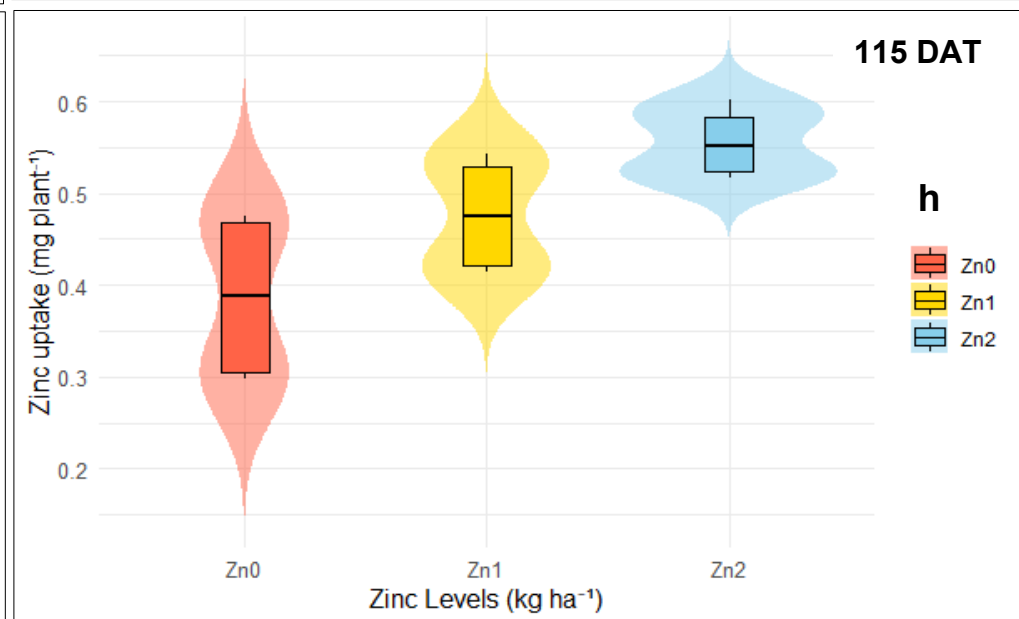
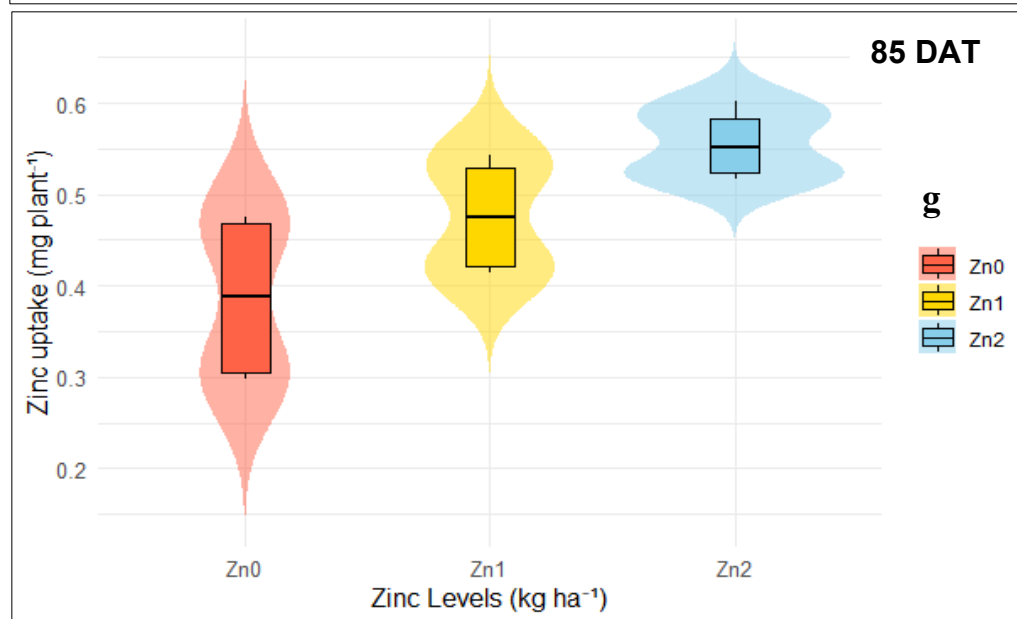
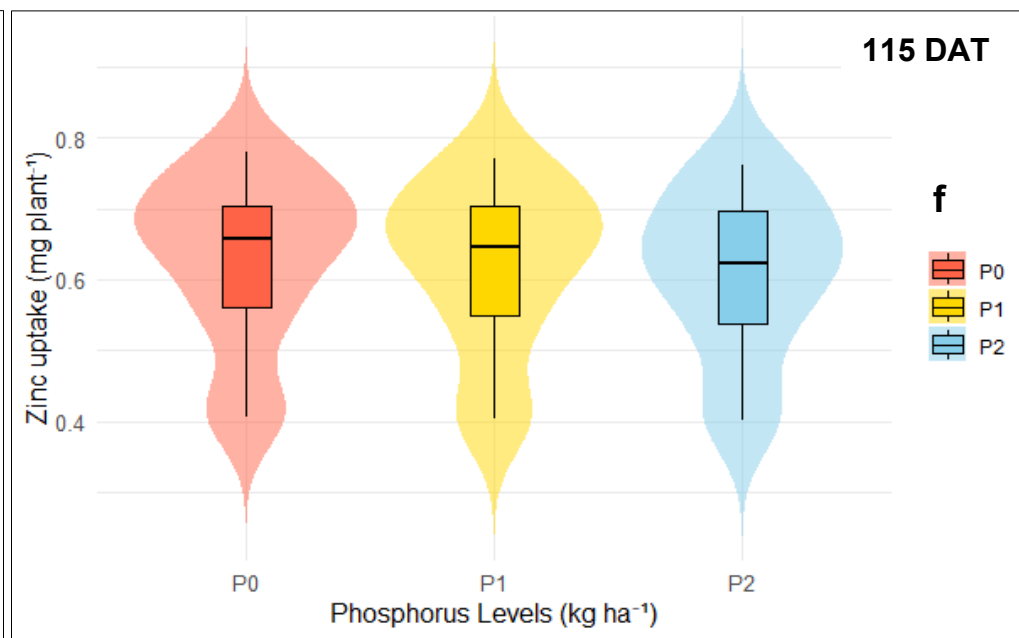
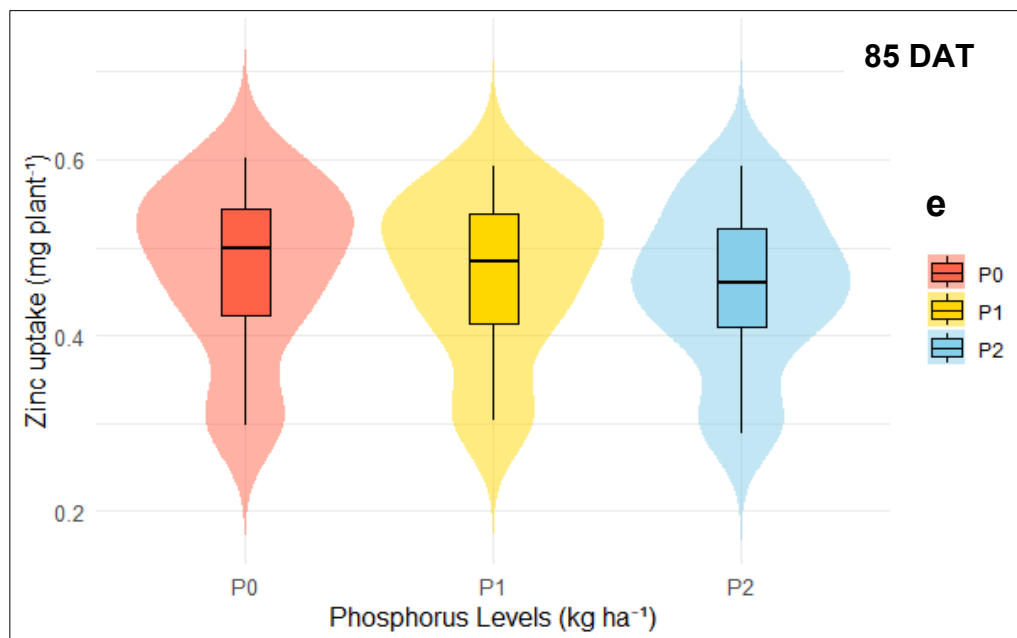
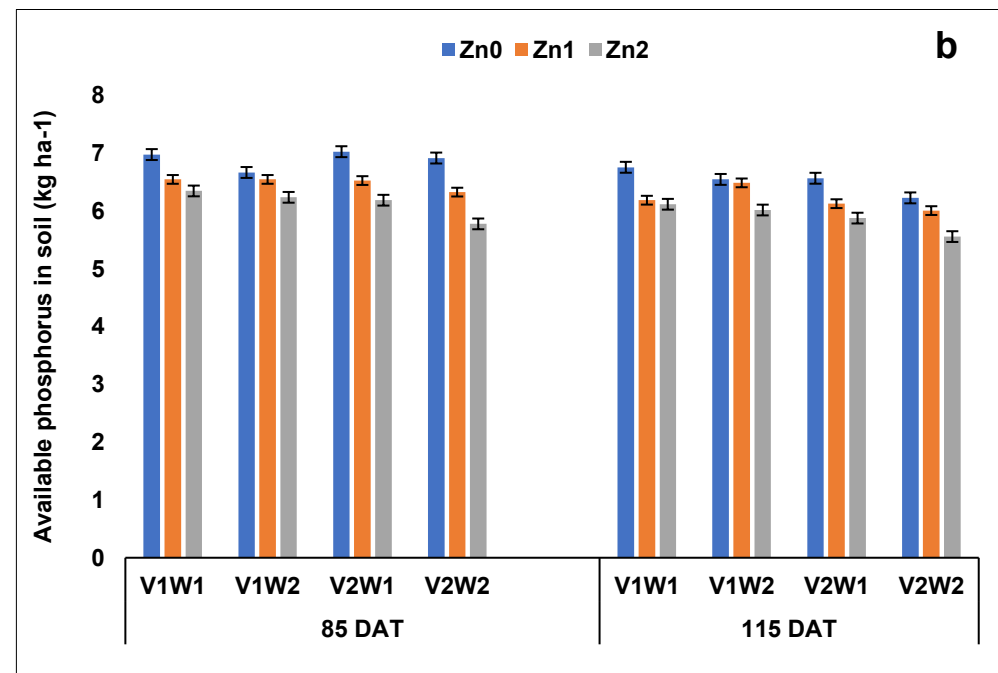
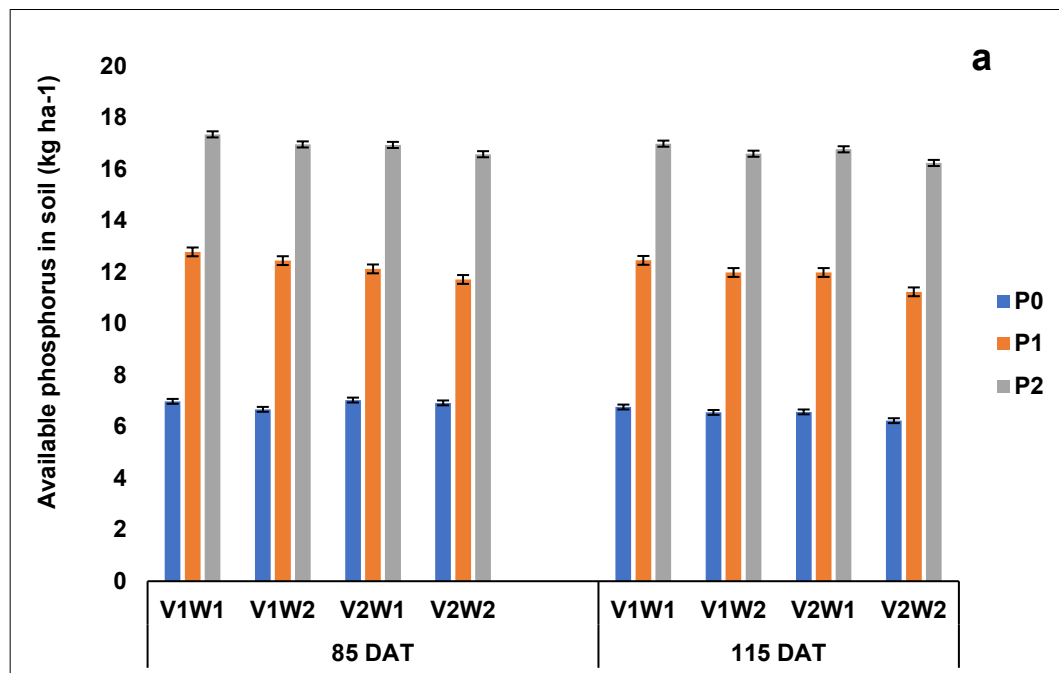


Fig.2. Violin-box plots on the uptake statistics of phosphorus and zinc by plants under the single effect of phosphorus and zinc application at the both 85 DAT and 115 DAT stages. a = Uptake of phosphorus at different levels of phosphorus application at 85 DAT, b = Uptake of phosphorus at different levels of phosphorus application at 115 DAT, c= Uptake of phosphorus at different levels of Zinc application at 85 DAT, d = Uptake of phosphorus at different levels of Zinc application at 115 DAT, e= Uptake of Zinc at different levels of phosphorus application at 85 DAT, f = Uptake of Zinc at different levels of phosphorus application at 115 DAT, g = Uptake of Zinc at different levels of Zinc application at 85 DAT, h = Uptake of Zinc at different levels of Zinc application at 115 DAT. DAT = Days after Transplantation. (Pooled mean of two consecutive years has been considered here).



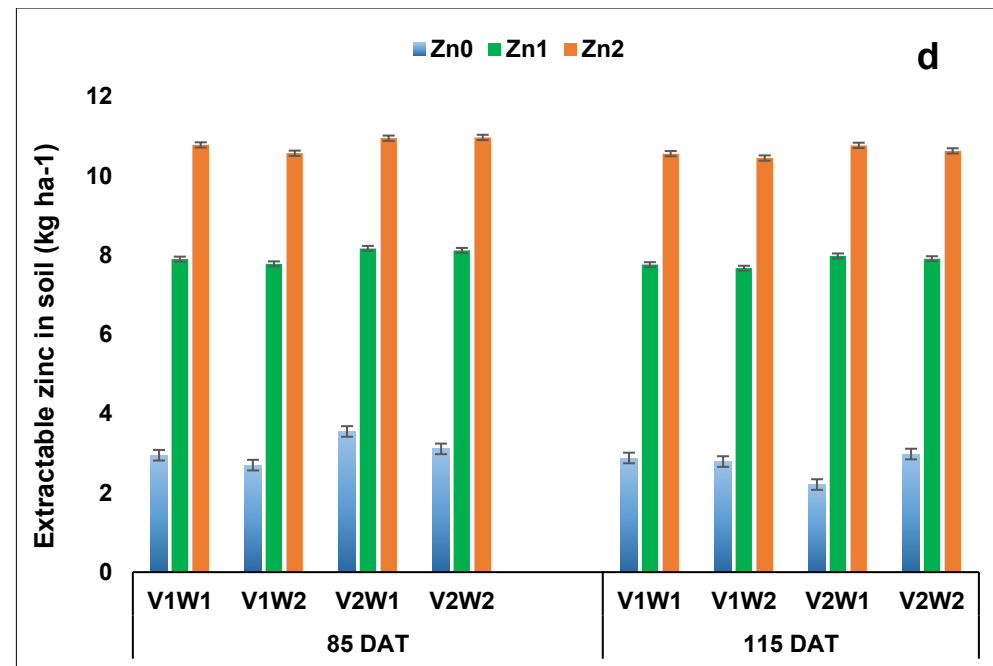
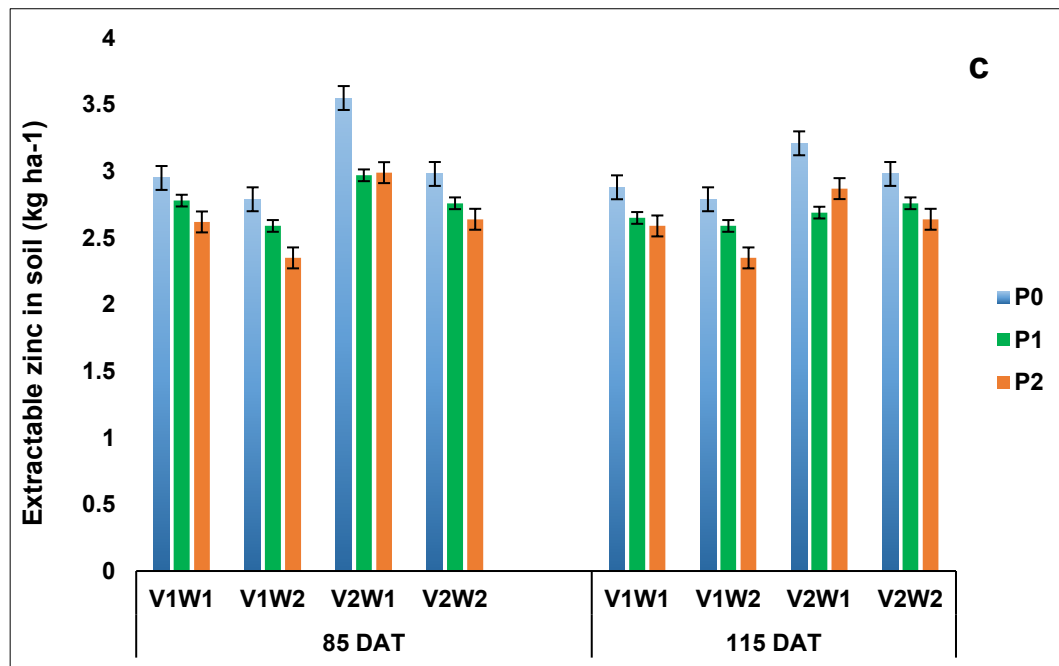


Fig.3. Single effect of phosphorus (a & b) and zinc (c & d) on both of their availability in soils after 85 DAT and 115 DAT under different moisture regimes for two different rice cultivars. P_0 = 0 P, P_1 = 45 kg P ha⁻¹, P_2 = 60 kg ha⁻¹; Zn_0 = 0, Zn_1 = 12.5 kg Zn ha⁻¹, Zn_2 = 25 kg Zn ha⁻¹, W_1 = Continuous Flooding, W_2 = 50% maximum water holding capacity; DAT = Days after Transplantation; V_1 = DRR Dhan 45, V_2 = IR 64. Error bars signify standard error of mean. (Pooled mean of two consecutive years has been considered here).

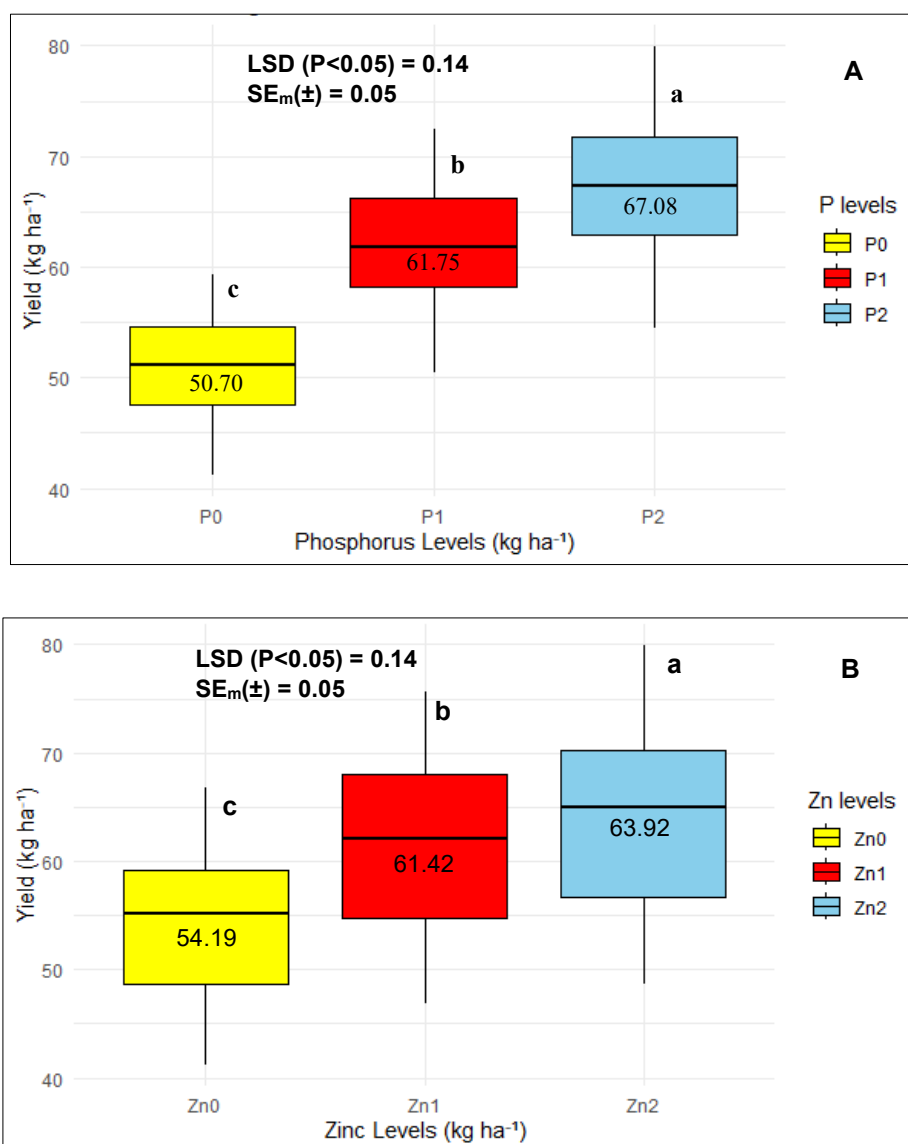


Fig.4. Violin-box plots on the yield statistics of rice under the single effect of phosphorus and zinc application. A = Single effect of Phosphorus application on the yield performance of rice; B = Single effect of Zinc application on the yield performance of rice. Values with different alphabets are significantly different from each other according to the DMRT test ($P < 0.05$). Each value is the mean of three replications.

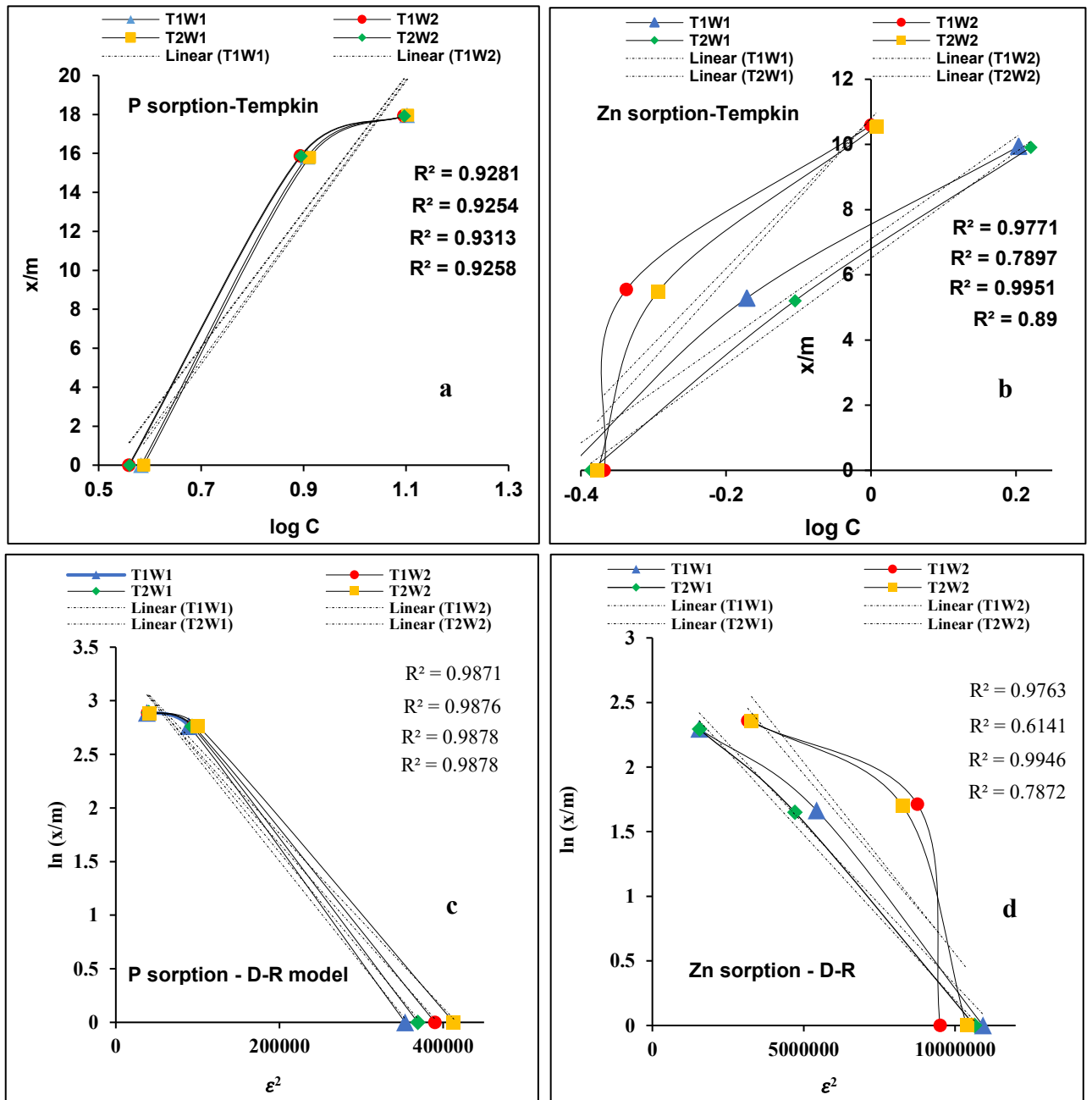


Fig.5. Curve fitting (linear) of the sorption data of phosphorus and zinc through several isotherm models under different temperature and moisture regimes. T_1 = at 298 K temperature, T_2 = at 308 K temperature; W_1 = Continuous Flooding, W_2 = 50% maximum water holding capacity; R^2 = Coefficient of Determination (indicator of goodness of model fitness), x/m = quantity of adsorbate per unit quantity of adsorbent; C = Equilibrium concentration of ions present in soil solution, ϵ = Polanyi potential. a = Temkin isotherm for phosphorus sorption; b = Temkin isotherm for zinc sorption; c = Dubinin–Radushkevich (D-R) isotherm for phosphorus sorption; d = Dubinin–Radushkevich (D-R) isotherm for zinc sorption. (Pooled mean of two consecutive years has been considered here).

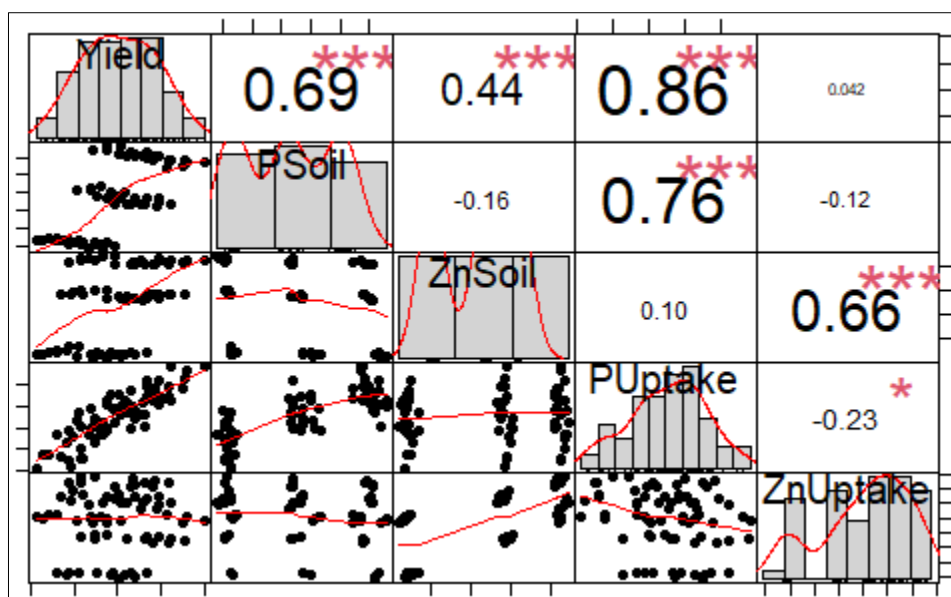


Fig.6. Pearson correlation plot between yield, uptakes and soil availability of P and Zn (***) = Significance level at $P < 0.001$; ** = Significance level at $P < 0.01$; * = Significance level at $P < 0.05$)

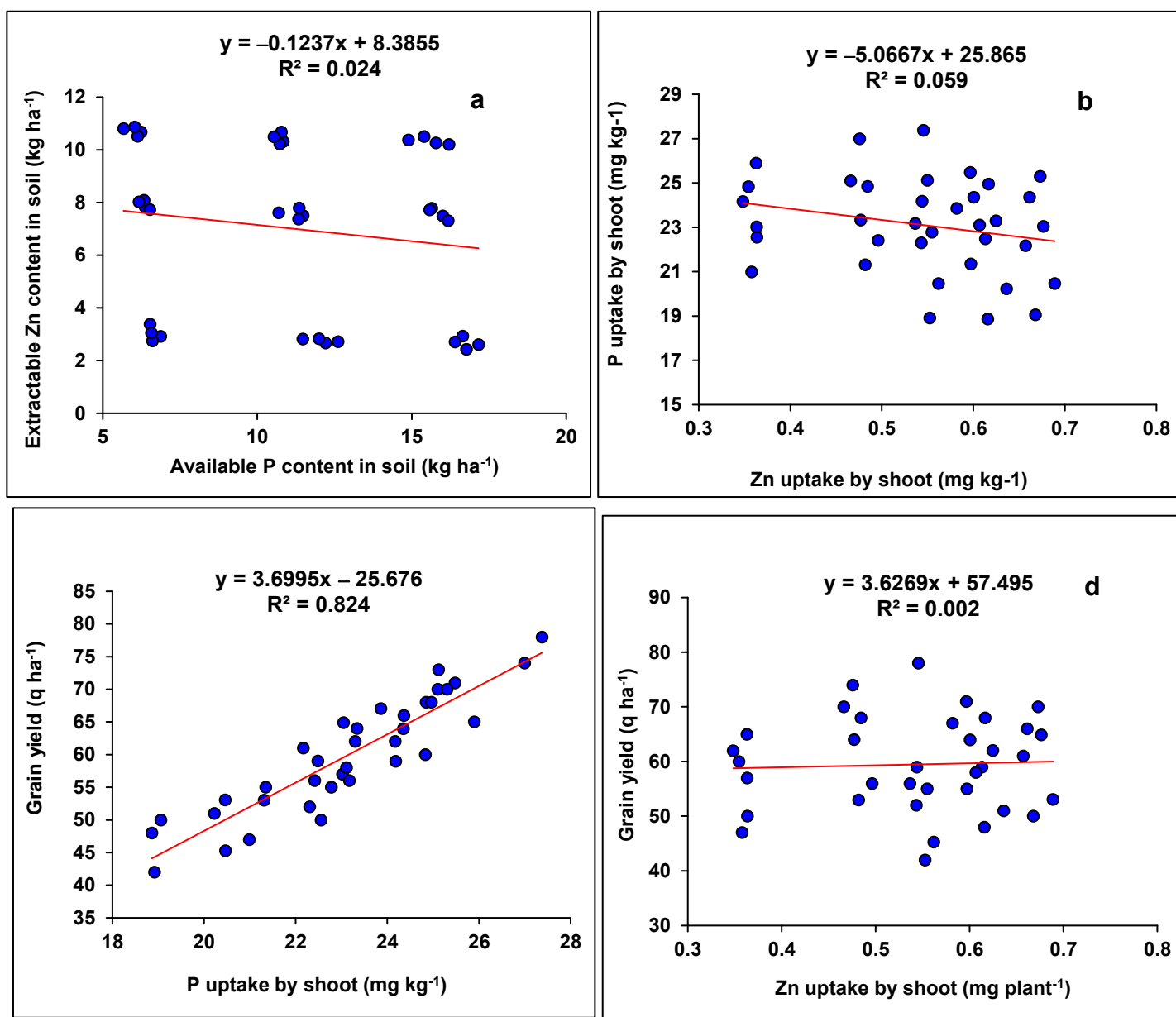


Fig.7. Simple linear regression between yield, uptakes and soil availability of P and Zn. A = Scatter plot between the soil availability of P and Zn; b = Scatter plot between P and Zn uptakes by shoot; c = Scatter plot grain yield and P uptake by shoot; d = Scatter plot between grain yield and Zn uptake by shoot;

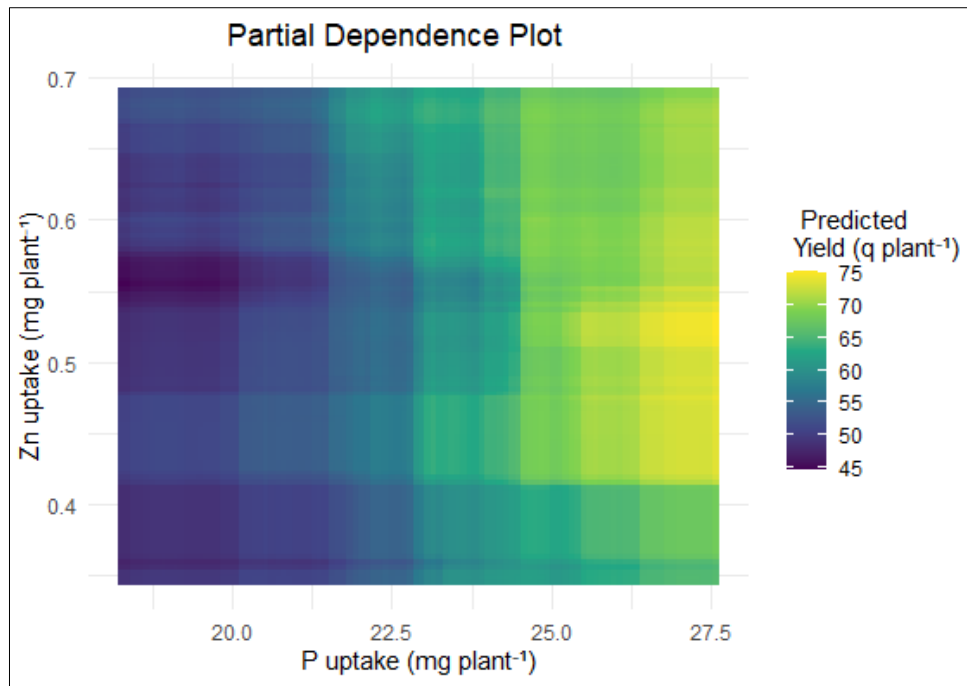


Fig.8. The dependence of predicted grain yield on the uptakes of P and Zn by shoot and *via Partial Dependence Plot (PDP) heatmap*

Table 1. Treatment Details of the Experiment

Treatments	Treatment Details
Zn ₀ P ₀ V ₁ W ₁	120 kg N + 60 kg K per ha + DRR Dhan 45 + Flooding
Zn ₀ P ₀ V ₁ W ₂	120 kg N + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₀ P ₀ V ₂ W ₁	120 kg N + 60 kg K per ha + IR 64 + Flooding
Zn ₀ P ₀ V ₂ W ₂	120 kg N + 60 kg K per ha + IR 64 + 50% WHC _{max}
Zn ₀ P ₁ V ₁ W ₁	120 kg N + 45 kg P + 60 kg K per ha + DRR Dhan 45 + Flooding
Zn ₀ P ₁ V ₁ W ₂	120 kg N + 45 kg P + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₀ P ₁ V ₂ W ₁	120 kg N + 45 kg P + 60 kg K per ha + IR 64 + Flooding
Zn ₀ P ₁ V ₂ W ₂	120 kg N + 45 kg P + 60 kg K per ha + IR 64 + 50% WHC _{max}
Zn ₀ P ₂ V ₁ W ₁	120 kg N + 60 Kg P + 60 kg K per ha + DRR Dhan 45 + Flooding
Zn ₀ P ₂ V ₁ W ₂	120 kg N + 60 Kg P + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₀ P ₂ V ₂ W ₁	120 kg N + 60 Kg P + 60 kg K per ha + IR 64 + Flooding
Zn ₀ P ₂ V ₂ W ₂	120 kg N + 60 Kg P + 60 kg K per ha + IR 64 + 50% WHC _{max}
Zn ₁ P ₀ V ₁ W ₁	120 kg N +12.5 kg Zn + 60 kg K per ha + DRR Dhan 45 + Flooding
Zn ₁ P ₀ V ₁ W ₂	120 kg N +12.5 kg Zn + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₁ P ₀ V ₂ W ₁	120 kg N +12.5 kg Zn + 60 kg K per ha + IR 64 + Flooding
Zn ₁ P ₀ V ₂ W ₂	120 kg N +12.5 kg Zn + 60 kg K per ha + IR 64 + 50% WHC _{max}
Zn ₁ P ₁ V ₁ W ₁	120 kg N +12.5 kg Zn + 45 Kg P + 60 kg K per ha + DRR Dhan 45 + Flooding
Zn ₁ P ₁ V ₁ W ₂	120 kg N +12.5 kg Zn + 45 Kg P + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₁ P ₁ V ₂ W ₁	120 kg N +12.5 kg Zn + 45 Kg P + 60 kg K per ha + IR 64 + Flooding
Zn ₁ P ₁ V ₂ W ₂	120 kg N +12.5 kg Zn + 45 Kg P + 60 kg K per ha + IR 64 + 50% WHC _{max}
Zn ₁ P ₂ V ₁ W ₁	120 kg N +12.5 kg Zn + 60 kg P + 60 kg K per ha DRR Dhan 45 + Flooding
Zn ₁ P ₂ V ₁ W ₂	120 kg N +12.5 kg Zn + 60 kg P + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₁ P ₂ V ₂ W ₁	120 kg N +12.5 kg Zn + 60 kg P + 60 kg K per ha + IR 64 + Flooding
Zn ₁ P ₂ V ₂ W ₂	120 kg N +12.5 kg Zn + 60 kg P + 60 kg K per ha + IR 64 + 50% WHC _{max}
Zn ₂ P ₀ V ₁ W ₁	120 kg N + 25 kg Zn + 60 kg K per ha + DRR Dhan 45 + Flooding
Zn ₂ P ₀ V ₁ W ₂	120 kg N + 25 kg Zn + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₂ P ₀ V ₂ W ₁	120 kg N + 25 kg Zn + 60 kg K per ha + IR 64 + Flooding
Zn ₂ P ₀ V ₂ W ₂	120 kg N + 25 kg Zn + 60 kg K per ha + IR 64 + 50% WHC _{max}
Zn ₂ P ₁ V ₁ W ₁	120 kg N + 25 kg Zn + 45 kg P + 60 kg K per ha + DRR Dhan 45 + Flooding
Zn ₂ P ₁ V ₁ W ₂	120 kg N + 25 kg Zn + 45 kg P + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₂ P ₁ V ₂ W ₁	120 kg N + 25 kg Zn + 45 kg P + 60 kg K per ha + IR 64 + Flooding
Zn ₂ P ₁ V ₂ W ₂	120 kg N + 25 kg Zn + 45 kg P + 60 kg K per ha+ IR 64 + 50% WHC _{max}
Zn ₂ P ₂ V ₁ W ₁	120 kg N + 25 kg Zn + 60 kg P + 60 kg K per ha + DRR Dhan 45 + Flooding
Zn ₂ P ₂ V ₁ W ₂	120 kg N + 25 kg Zn + 60 kg P + 60 kg K per ha + DRR Dhan 45 + 50% WHC _{max}
Zn ₂ P ₂ V ₂ W ₁	120 kg N + 25 kg Zn + 60 kg P + 60 kg K per ha + IR 64 + Flooding
Zn ₂ P ₂ V ₂ W ₂	120 kg N + 25 kg Zn + 60 kg P + 60 kg K per ha + IR 64 + 50% WHC _{max}

[N = Nitrogen; P = Phosphorus; K = Potassium; Zn = Zinc; kg = kilogram; WHC_{max} = Maximum water holding capacity]

Table 2. Physico-chemical characterization of the initial soil

pH _{2.5}	5.38
EC _{2.5} (dSm ⁻¹)	0.24
SOC	0.40
CEC [cmol (p ⁺) kg ⁻¹]	6.10
Soil Moisture Content (%)	16.50
Available N ((kg ha ⁻¹))	146.39
Available P ₂ O ₅ (kg ha ⁻¹)	19.61
Extractable Zinc (mg kg ⁻¹)	0.96
Available K ₂ O (kg ha ⁻¹)	121.17
Sand (%)	54.81
Silt (%)	32.26
Clay (%)	12.93
Textural class	Sandy loam

[EC = Electrical conductivity; CEC = Cation Exchange Capacity]

Table 3. Combine effects of zinc and phosphorus on phosphorus uptake by plant (mg/Plant) under different soil moisture regimes at two different growth stages of two rice cultivars

Treatments	85 DAT					115 DAT				
	V ₁ W ₁	V ₁ W ₂	V ₂ W ₁	V ₂ W ₂	Mean	V ₁ W ₁	V ₁ W ₂	V ₂ W ₁	V ₂ W ₂	Mean
P₀Zn₀	16.27	15.01	18.03	16.56	16.47	24.67	22.82	27.08	25.41	25.00
P₁Zn₀	18.57	18.24	20.33	18.32	18.87	26.99	26.36	29.34	27.73	27.61
P₂Zn₀	20.11	19.34	21.46	19.67	20.15	28.26	27.01	30.33	28.67	28.57
P₀Zn₁	16.07	14.42	17.99	16.84	16.33	24.38	23.31	26.84	25.79	25.08
P₁Zn₁	19.32	18.29	20.59	18.63	19.21	27.29	26.68	29.11	28.04	27.78
P₂Zn₁	20.88	20.40	22.68	20.42	21.10	29.03	28.31	31.31	29.77	29.61
P₀Zn₂	16.93	14.99	18.72	16.51	16.79	23.99	23.13	27.49	26.18	25.20
P₁Zn₂	18.82	18.49	21.09	19.21	19.40	27.27	25.85	29.86	28.51	27.87
P₂Zn₂	21.53	20.46	22.97	20.29	21.31	29.07	28.25	31.78	29.96	29.77
Mean	18.72	17.74	20.43	18.49		26.77	25.75	29.24	27.78	
Factors	LSD (P<0.05)		SE_m (±)			LSD (P<0.05)		SE_m (±)		
P	0.56***		0.19			0.96***		0.33		
Zn	0.56*		0.19			NS		0.33		
W	0.46***		0.16			0.78***		0.27		
V	0.46***		0.16			0.78***		0.27		
P × Zn	NS		0.34			NS		0.58		
P × W	NS		0.27			NS		0.47		
Zn × W	NS		0.27			NS		0.47		
P × V	NS		0.27			NS		0.47		
Zn × V	NS		0.27			NS		0.47		
V × W	0.64*		0.22			NS		0.39		
P × Zn × W	NS		0.48			NS		0.82		
P × Zn × V	NS		0.48			NS		0.82		
P × V × W	NS		0.39			NS		0.67		
Zn × V × W	NS		0.39			NS		0.67		
P × Zn × V × W	NS		0.58			NS		1.00		

[P₀= 0 P, P₁= 45 kg P ha⁻¹, P₂ = 60 kg ha⁻¹; Zn₀ = 0, Zn₁ = 12.5 kg Zn ha⁻¹, Zn₂ = 25 kg Zn ha⁻¹, W₁ = Continuous Flooding, W₂ = 50% maximum water holding capacity; DAT = Days after Transplantation; V₁ = DRR Dhan 45, V₂ = IR 64. LSD = Least Significant Difference; SEM = Standard error of mean; *** = Significance level at P<0.001; ** = Significance level at P<0.01; * = Significance level at P<0.05; NS= Non-significant. Each value is a mean of three replications. Pooled mean of two consecutive years has been considered here]

Table 4. Combine effects of zinc and phosphorus on zinc uptake by plant (mg/Plant) under different soil moisture regimes at two different growth stages of two rice cultivars

Treatments	85 DAT					115 DAT				
	V ₁ W ₁	V ₁ W ₂	V ₂ W ₁	V ₂ W ₂	Mean	V ₁ W ₁	V ₁ W ₂	V ₂ W ₁	V ₂ W ₂	Mean
P₀Zn₀	0.4788	0.4708	0.3134	0.3002	0.3908	0.6452	0.6344	0.4139	0.4055	0.5248
P₁Zn₀	0.4768	0.4630	0.3035	0.3139	0.3893	0.6401	0.6299	0.4050	0.4150	0.5225
P₂Zn₀	0.4632	0.4584	0.3113	0.2945	0.3819	0.6249	0.6149	0.4146	0.4028	0.5143
P₀Zn₁	0.5524	0.5372	0.4260	0.4170	0.4832	0.7207	0.6945	0.5664	0.5470	0.6322
P₁Zn₁	0.5419	0.5282	0.4166	0.4117	0.4746	0.7129	0.6982	0.5531	0.5426	0.6267
P₂Zn₁	0.5317	0.5126	0.4114	0.4041	0.4650	0.7101	0.6867	0.5403	0.5282	0.6163
P₀Zn₂	0.5994	0.5772	0.5263	0.5190	0.5555	0.7784	0.7549	0.6809	0.6757	0.7225
P₁Zn₂	0.5287	0.5634	0.5207	0.5050	0.5295	0.7725	0.7532	0.6734	0.6582	0.7143
P₂Zn₂	0.5812	0.5709	0.4719	0.4518	0.5190	0.7608	0.7523	0.6193	0.6481	0.6951
Mean	0.5282	0.5202	0.4112	0.4019		0.7073	0.6910	0.5408	0.5359	
Factors	LSD (P<0.05)		SE_m (±)			LSD (P<0.05)		SE_m (±)		
P	0.0059***		0.0020			0.0059***		0.0020		
Zn	0.0059***		0.0020			0.0059***		0.0021		
W	0.0049***		0.0017			0.0026***		0.0009		
V	0.0049***		0.007			0.0026***		0.0009		
P × Zn	0.0103*		0.0035			0.0055**		0.0036		
P × W	NS		0.0029			0.0045*		0.0029		
Zn × W	NS		0.0029			0.0045**		0.0029		
P × V	0.0084*		0.0029			0.0045**		0.0016		
Zn × V	0.0084***		0.0029			0.0045***		0.0029		
V × W	NS		0.0023			0.0036***		0.0		
P × Zn × W	NS		0.0051			0.0078***		0.0050		
P × Zn × V	0.014***		0.0050			0.0027***		0.0078		
P × V × W	NS		0.0041			NS		0.0022		
Zn × V × W	NS		0.0041			NS		0.0022		
P × Zn × V × W	NS		0.0071			0.0011*		0.0072		

[P₀= 0 P, P₁= 45 kg P ha⁻¹, P₂ = 60 kg ha⁻¹; Zn₀= 0, Zn₁ = 12.5 kg Zn ha⁻¹, Zn₁= 25 kg Zn ha⁻¹, W₁ = Continuous Flooding, W₂ = 50% maximum water holding capacity; DAT = Days after Transplantation; V₁ = DRR Dhan 45, V₂ = IR 64. LSD = Least Significant Difference; SE_m = Standard error of mean; *** = Significance level at P<0.001; ** = Significance level at P<0.01; * = Significance level at P<0.05; N.S.= Non-significant. Each value is a mean of three replications. Pooled mean of two consecutive years has been considered here]

Table 5. Combine effects of zinc and phosphorus on available phosphorus (kg ha⁻¹) in soil under different soil moisture regimes at two different growth stages of two rice cultivars

Treatments	85 DAT					115 DAT				
	V ₁ W ₁	V ₁ W ₂	V ₂ W ₁	V ₂ W ₂	Mean	V ₁ W ₁	V ₁ W ₂	V ₂ W ₁	V ₂ W ₂	Mean
P₀Zn₀	6.98	6.67	7.03	6.92	6.90	6.76	6.55	6.57	6.23	6.53
P₁Zn₀	12.78	12.44	12.12	11.71	12.26	12.45	11.98	11.98	11.23	11.91
P₂Zn₀	17.34	16.95	16.93	16.57	16.95	16.98	16.59	16.76	16.23	16.64
P₀Zn₁	6.55	6.55	6.53	6.33	6.49	6.19	6.49	6.13	6.01	6.21
P₁Zn₁	11.74	11.56	11.62	10.92	11.46	11.23	11.11	11.08	10.46	10.97
P₂Zn₁	16.23	16.37	15.91	15.97	16.12	15.78	15.99	15.38	15.19	15.59
P₀Zn₂	6.35	6.24	6.19	5.78	6.14	6.12	6.02	5.88	5.56	5.89
P₁Zn₂	10.98	10.81	10.99	10.78	10.89	10.69	10.65	10.56	10.29	10.50
P₂Zn₂	15.93	16.23	15.78	15.01	15.74	15.63	16.17	15.01	14.78	15.40
Mean	11.65	11.54	11.45	11.11		11.31	11.28	11.04	10.66	
Factors	LSD (P<0.05)		SE_m (±)			LSD (P<0.05)		SE_m (±)		
P	0.07***		0.03			0.06***		0.02		
Zn	0.07***		0.03			0.06***		0.02		
W	0.04***		0.01			0.03***		0.01		
V	0.04***		0.01			0.03***		0.01		
P × Zn	0.13***		0.04			0.10***		0.04		
P × W	0.07***		0.03			0.06***		0.02		
Zn × W	0.07*		0.03			0.06**		0.02		
P × V	0.07***		0.03			0.06***		0.02		
Zn × V	0.07***		0.03			0.06***		0.02		
V × W	0.04***		0.01			0.03***		0.01		
P × Zn × W	0.13***		0.04			0.10***		0.04		
P × Zn × V	0.13***		0.04			0.10***		0.04		
P × V × W	0.07***		0.03			0.06***		0.02		
Zn × V × W	0.07***		0.03			0.06***		0.02		
P × Zn × V × W	0.13***		0.04			0.10***		0.04		

[P₀= 0 P, P₁= 45 kg P ha⁻¹, P₂ = 60 kg ha⁻¹; Zn₀ = 0, Zn₁ = 12.5 kg Zn ha⁻¹, Zn₂ = 25 kg Zn ha⁻¹, W₁ = Continuous Flooding, W₂ = 50% maximum water holding capacity; DAT = Days after Transplantation; V₁ = DRR Dhan 45, V₂ = IR 64. LSD = Least Significant Difference; SEM = Standard error of mean; *** = Significance level at P<0.001; ** = Significance level at P<0.01; * = Significance level at P<0.05; NS= Non-significant. Each value is a mean of three replications. Pooled mean of two consecutive years has been considered here]

Table 6. Combine effects of zinc and phosphorus on extractable-Zinc (kg ha⁻¹) in soil under different soil moisture regimes at two different growth stages of two rice cultivars

Treatments	85 DAT					115 DAT				
	V ₁ W ₁	V ₁ W ₂	V ₂ W ₁	V ₂ W ₂	Mean	V ₁ W ₁	V ₁ W ₂	V ₂ W ₁	V ₂ W ₂	Mean
P₀Zn₀	2.95	2.70	3.55	3.11	3.08	2.88	2.79	3.21	2.98	2.97
P₁Zn₀	2.78	2.74	2.97	2.87	2.84	2.65	2.59	2.69	2.76	2.67
P₂Zn₀	2.62	2.49	2.99	2.78	2.72	2.59	2.35	2.87	2.64	2.61
P₀Zn₁	7.90	7.78	8.17	8.12	7.99	7.76	7.67	7.98	7.91	7.83
P₁Zn₁	7.56	7.45	7.79	7.65	7.61	7.43	7.28	7.78	7.56	7.51
P₂Zn₁	7.53	7.38	7.89	7.89	7.67	7.45	7.23	7.67	7.55	7.48
P₀Zn₂	10.78	10.57	10.95	10.97	10.82	10.56	10.45	10.77	10.63	10.60
P₁Zn₂	10.39	10.32	10.78	10.56	10.51	10.23	10.11	10.56	10.43	10.33
P₂Zn₂	10.29	10.23	10.45	10.39	10.34	10.24	10.17	10.56	10.34	10.33
Mean	6.98	6.85	7.28	7.15		6.87	6.74	7.12	6.98	
Factors	LSD (P<0.05)		SE_m (±)			LSD (P<0.05)		SE_m (±)		
P	0.05***		0.02			0.06***		0.02		
Zn	0.05***		0.02			0.06***		0.02		
W	0.06***		0.02			0.08***		0.03		
V	0.06***		0.02			0.08***		0.03		
P × Zn	0.03***		0.01			NS		0.01		
P × W	0.04*		0.01			NS		0.02		
Zn × W	0.04***		0.01			NS		0.02		
P × V	0.04***		0.01			NS		0.02		
Zn × V	0.04**		0.01			NS		0.02		
V × W	NS		0.02			NS		0.02		
P × Zn × W	0.02***		0.01			0.03**		0.01		
P × Zn × V	0.02***		0.01			0.03**		0.01		
P × V × W	0.03*		0.01			NS		0.01		
Zn × V × W	0.03**		0.01			NS		0.01		
P × Zn × V × W	0.01**		0.01			NS		0.01		

[P₀= 0 P, P₁= 45 kg P ha⁻¹, P₂ = 60 kg ha⁻¹; Zn₀ = 0, Zn₁ = 12.5 kg Zn ha⁻¹, Zn₂= 25 kg Zn ha⁻¹, W₁ = Continuous Flooding, W₂ = 50% maximum water holding capacity; DAT = Days after Transplantation; V₁ = DRR Dhan 45, V₂ = IR 64. LSD = Least Significant Difference; SEM = Standard error of mean; *** = Significance level at P<0.001; ** = Significance level at P<0.01; * = Significance level at P<0.05; NS= Non-significant. Pooled mean of two consecutive years has been considered here. Each value is a mean of three replications. Pooled mean of two consecutive years has been considered here]

Table 7. Estimated isotherm constants for phosphorus and zinc sorption under different temperature and moisture regimes

Treatments	Freundlich Adsorption Isotherm Model				Langmuir Adsorption Isotherm Model				
	Isotherm parameters		Model fitness		Isotherm parameters		Model fitness		
	K _F	n	Model equation (linear)	R ²	Q _m	K _L	Model equation (linear)	R ²	
P-T ₁ W ₁	24.138	0.393	y = 2.5474x – 1.3827	0.89	12.610	0.324	y = 0.0793x – 0.2446	0.92	
P-T ₁ W ₂	18.707	0.406	y = 2.4607x – 1.272	0.88	12.804	0.346	y=0.0781x – 0.2256	0.93	
P-T ₂ W ₁	25.686	0.389	y = 2.5674x – 1.4097	0.89	12.547	0.332	y = 0.0797x – 0.2494	0.93	
P-T ₂ W ₂	18.963	0.406	y = 2.4634x – 1.2779	0.88	12.804	0.346	y = 0.0781x – 0.227	0.92	
			Mean	0.86			Mean	0.93	
Zn-T ₁ W ₁	5.9089	0.654	y = 1.5287x + 0.7715	0.87	9.183	544.500	y = 0.1089x – 0.0002	0.66	
Zn-T ₁ W ₂	11.337	0.506	y = 1.9768x + 1.0545	0.58	9.862	21.574	y = 0.1014x – 0.0047	0.62	
Zn-T ₂ W ₁	11.874	0.454	y = 2.2036x + 1.0746	0.71	8.795	54.143	y = 0.1137x – 0.0021	0.40	
Zn-T ₂ W ₂	5.215	0.617	y = 1.6218x + 0.7173	0.92	9.217	14.662	y = 0.1085x – 0.0074	0.41	
			Mean	0.77			Mean	0.52	
Tempkin Adsorption Isotherm Model					Dubinin–Radushkevich (D-R) Isotherm Model				
Treatments	Isotherm Parameters		Model Fitness		Isotherm Parameters				Model Fitness
	A _T	b _T	Model equation (linear)	R ²	β	E	q _m	Model equation (linear)	R ²
P-T ₁ W ₁	3.560	163.523	y = 36.064x – 19.887	0.93	–1×10 ^{–5}	223.6	30.551	y = –1×10 ^{–5} x + 3.4194	0.99
P-T ₁ W ₂	3.355	169.40	y = 34.813x – 18.3	0.92	–9×10 ^{–6}	235.7	29.542	y = –9×10 ^{–6} x + 3.3858	0.98
P-T ₂ W ₁	3.612	162.313	y = 36.333x – 20.264	0.93	–9×10 ^{–6}	235.7	30.646	y = –9×10 ^{–6} x + 3.4225	0.97
P-T ₂ W ₂	3.368	169.302	y = 34.833x – 18.372	0.92	–8×10 ^{–6}	250	29.533	y = –8×10 ^{–6} x + 3.3855	0.98
			Mean	0.93				Mean	0.98
Zn-T ₁ W ₁	2.844	376.994	y = 15.643x + 7.1015	0.98	–2×10 ^{–7}	1581.1	16.530	y = –2×10 ^{–7} x + 2.8052	0.98
Zn-T ₁ W ₂	2.941	255.850	y = 23.05x + 10.799	0.79	–3×10 ^{–7}	1581.1	27.718	y = –3×10 ^{–7} x + 3.3221	0.61
Zn-T ₂ W ₁	2.510	362.087	y = 16.287x + 6.5094	0.99	–3×10 ^{–7}	1291	15.724	y = –3×10 ^{–7} x + 2.7552	0.99
Zn-T ₂ W ₂	2.743	239.465	y = 24.627x + 10.792	0.89	–3×10 ^{–7}	1291.0	33.606	y = –3×10 ^{–7} x + 3.5147	0.79
			Mean	0.92				Mean	0.85

[P = Phosphorus levels, Zn = Zinc levels; T₁ = at 298 K temperature, T₂ = at 308 K temperature; W₁ = Continuous Flooding, W₂ = 50% maximum water holding capacity; ΔG = Gibbs free energy (KJ mol^{–1}); x/m = Amount of adsorbate per unit quantity of adsorbent (μg g^{–1}); C = Equilibrium concentration of ions present in soil solution; K_F = Freundlich constant related to adsorption capacity; 1/n = Freundlich constant related to adsorption intensity; Q_m = Langmuir adsorption maxima (μg g^{–1}); K_L = Langmuir constant related to binding energy (L mol^{–1}); R = Universal gas constant (8.314 J/mol K); T = Absolute temperature; A_T = Maximum Binding energy (L g^{–1}); B_T = Constant related to the heat of adsorption; b_T = Tempkin isotherm constant; q_m = Dubinin–Radushkevich (D-R) constant related to the adsorption capacity; β = Constant related to mean free energy of adsorption (mol²/KJ²); ε = Polanyi Potential, E = free energy of adsorption (KJ mol^{–1}). Pooled mean of two consecutive years has been considered here]

Table 8. Multiple Linear Regression based prediction of grain yield based on nutrient uptake and soil nutrient status (n=72)

Prediction Equations	R ²	Adj. R ²	SE (est.)
$Y = 11.260 + 1.530 \times P_{Uptake}^{***} + 1.738 \times Zn_{Soil}^{**} + 1.032 \times P_{Soil}^* - 19.440$ $\times Zn_{Uptake}^*$	0.92	0.92	2.58
$Y = -8.233 + 2.216 \times P_{Uptake}^{***} + 1.221 \times Zn_{Soil}^{**} + 0.740 \times P_{Soil}^*$	0.90	0.90	0.83
$Y = -22.544 + 3.261 \times P_{Uptake}^{***} + 1.002 \times Zn_{Soil}^{**}$	0.86	0.86	3.36
$Y = -18.896 + 3.406 \times P_{Uptake}^{***}$	0.73	0.73	4.63

[Regression models were developed using stepwise multiple linear regression to predict grain yield. Y: Grain yield; Coefficients were selected based on significance (P<0.05) and model fitness indicators such as Coefficient of Determination (R²), Adjusted R² and Standard Error of the Estimate. ***p ≤ 0.001 → very highly significant; **p ≤ 0.01 → highly significant; *p ≤ 0.05 → significant]

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplimentaryFigures.docx](#)
- [SupplimentaryTables.docx](#)