IJAFLS
e-ISSN: 2602-4381

International Journal of
Agriculture, Forestry and Life Sciences

Research Article Open access Int J Agric For Life Sci (2025) 9(2):83-92

The Interactive Effect of Flooding and Organic Matter Treatments on Phosphorus Adsorption on Calcareous Soils

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Citation
Ören, S., Uygur, V. (2025). The Interactive Effect of Flooding and Organic Matter Treatments on Phosphorus Adsorption on Calcareous Soils. Int J Agric For Life Sci., 9(2):83-92

Received :31 August 2025
Accepted :1 October 2025
Published Online :28 November 2025
Year: :2025
Volume :9
Issue :2 (December)
Pages :83-92

International Journal of Agriculture, Forestry and Life Sciences; Edit Publishing, Eskişehir, Türkiye.

Abstract

Phosphorus (P) availability in calcareous soils is limited due to strong adsorption and precipitation reactions, which hinder plant uptake and complicate nutrient management. This study explored how flooding duration (0–40 days) and farmyard manure (FYM) application (0 and 4 g per 100 g soil) affect P adsorption in five calcareous soils with varying physical and chemical properties. Using batch equilibrium experiments, P sorption was modelled with Freundlich and Langmuir isotherms. Flooding increased adsorption capacity, as indicated by higher KF and Smax values, due to redox-driven dissolution and re-precipitation of Fe/Mn oxides, which created more sorption sites. Initially, FYM reduced adsorption strength because of organic ligands and labile P inputs. However, with prolonged flooding, FYM enhanced adsorption through organo-mineral interactions and secondary oxide formation. Soil characteristics such as carbonate content, clay fraction, and organic matter influenced these effects. The modified Langmuir model provided the best fit, emphasizing the role of both native and added P in adsorption dynamics. Overall, the study shows that flooding and organic amendments interact to regulate P retention in calcareous soils, offering insights for sustainable phosphorus management under conditions of climate variability and increased waterlogging.

Key words
Adsorption parameters, waterlogging duration, Langmuir isotherm, Freundlich isotherm.

Introduction

Phosphorus (P) is a key macronutrient essential for plant growth and development, involved in energy transfer, signal transduction, and photosynthesis (Marschner, 2012). However, its availability in many soils—especially calcareous soils—is limited due to strong fixation and adsorption processes. Calcareous soils, typical of arid and semi-arid regions, are characterized by high calcium carbonate ($CaCO_3$) content and alkaline pH. These conditions promote the immobilization of added phosphorus through precipitation and adsorption into non-bioavailable pools (Uygur, 2009; Mahdi et al., 2019, 2023).

Phosphorus management in calcareous soils is further complicated by environmental factors such as flooding and the increasing use of organic amendments like farmyard manure (FYM), compost, and plant residues (Uygur and Karabatak, 2009; Pizzeghello et al., 2011, 2014; Zhang et al., 2021; Sundha et al., 2022). While individual effects of these factors have been studied, their interactive influence on P adsorption in calcareous soils with varying properties remains insufficiently explored.

P adsorption in calcareous soils is primarily governed by precipitation reactions with calcium and adsorption onto $CaCO_3$, Fe/Al/Mn oxides, and clay minerals (Uygur and Ince, 2020; Adnan et al., 2025; Kotb, 2025; Li et al., 2025). Under alkaline conditions, phosphate ions react with Ca^{2+} to form insoluble calcium phosphate minerals such as dicalcium phosphate dihydrate (DCPD), octacalcium phosphate (OCP), and hydroxyapatite (HAP), which significantly reduce P mobility and availability (Lindsay, 2001; Shen et al., 2019; Guo et al., 2025). High $CaCO_3$ content further increases reactive sorption sites, exacerbating P fixation (Uygur, 2009; Kotb, 2025). Although adsorption onto Fe/Al oxides and phyllosilicates also contributes to P retention, these mechanisms are often masked by dominant Ca-mediated precipitation (Torrent, 1997; Lombi et al., 2006; Mahdi et al., 2019).

Organic matter (OM) amendments are increasingly applied to improve soil fertility and P availability. FYM, compost, crop residues, and biochar influence P dynamics through multiple mechanisms: (i) low and high molecular weight organic acids released from OM compete with phosphate ions for sorption sites (Moradi et al., 2012; Oral and Uygur, 2018; Zahraeni and Uygur, 2024); (ii) organic ligands form stable complexes with Al^{3+}, Fe^{3+}, and Ca^{2+}, reducing precipitation of insoluble P compounds (Gypser and Freese, 2020; Chen et al., 2024); and (iii) OM serves as a reservoir of organic P that can be mineralized into plant-available forms via microbial activity (McLaughlin et al., 1988; Uygur and Karabatak, 2009).

Numerous studies have shown that OM additions reduce P adsorption and increase Olsen-P concentrations in calcareous soils. For instance, Hu et al. (2024) reported that long-term manure application enhanced P mobility and increased sorption saturation. Erro et al. (2010) found that compost and humic substances improved P availability by blocking sorption sites and altering the soil's chemical environment. The effectiveness of OM depends on factors such as C:N ratio, degree of humification, and solubility. Manure and compost, rich in soluble organic matter, tend to be more effective than straw or biochar. Mikajlo et al. (2024) noted that composted biochar contains higher dissolved organic carbon and microbial activity than biochar alone or biochar-compost mixtures, mitigating biochar's negative effects on plant growth. However, prolonged use of certain OM sources may lead to P accumulation and increase environmental risks (Kavvadias et al., 2014; Singh et al., 2025).

Flooding alters soil physical and chemical conditions, primarily through changes in redox potential, microbial activity, and nutrient solubility (Fageria et al., 2011; Oren et al., 2018). Under anaerobic conditions, Fe(III) and Mn(IV) are reduced to Fe(II) and Mn(II), respectively, leading to dissolution of Fe/Mn oxides and release of associated P into the soil solution (Adhami et al., 2012; Gypser and Freese, 2020). In calcareous soils, however, flooding effects are less straightforward due to dominant Ca-related processes. Anoxic–oxic cycles influence ionic speciation and surface properties, and the duration and frequency of flooding events determine the extent of P mobilization. Short-term flooding may have minimal impact, while prolonged anoxia can significantly alter P fractionation (Adhami et al., 2012). Soils with high OM content tend to show greater P release under flooding, suggesting a synergistic interaction between flooding and OM treatments.

Although the individual effects of OM and flooding have been widely studied, their combined impact is still emerging. Some studies indicate that OM-amended soils under flooded conditions exhibit enhanced P release due to microbial activity and chemical transformations. Liang et al. (2021) found that compost combined with water saturation significantly increased labile P fractions in calcareous soils. Zhou et al. (2022) reported that manure application followed by flooding shifted P from calcium-bound forms to more labile Fe/Al-bound forms, improving plant availability. Waterlogged soils during winter or rainy seasons may exhibit inter-fraction mobility and dissolution of Fe/Mn oxides, setting new conditions for the subsequent cropping season. However, there is limited understanding of P adsorption behavior during the drying phase following submergence in calcareous soils.

Balancing agronomic benefits and environmental risks of combined flooding and OM application is critical for sustainable nutrient management. While evidence supports the influence of both factors on P dynamics, their interactive effects—especially in the post-waterlogging period—remain poorly quantified. Therefore, this study aims to investigate the effects of waterlogging duration and FYM incorporation on P adsorption in calcareous soils with contrasting properties. The findings will contribute to improved P management strategies in calcareous soils, particularly under increasing climate variability and the likelihood of extreme moisture events.

Materials and Methods

Sampling site and soil properties

Five calcareous soils belongs to Entisols, Mollisols, Inceptisols, and Vertisols soil orders were sampled. Nomenclature classifications of the soil are: S1 Typic Haploxeroll, S2 Calcic Haploxeprept, S3 and S4 Typic Zerofluvent, and S5 Vertic Haploxeroll (Akgül et al., 2001). The plant cover at sampling were S1 and S2 cherry orchard, S3 peach orchard, S4 forest covered mainly juniper, and S5 corn.

The properties of these soils were determined using standard methods recommended for calcareous soils (Kacar, 2014) (Table 1). In compliance with TSE ISO 11047 (2015), the soil samples were wet-digested using aqua regia ($HCl:HNO_3$, 3:1, V/V) to determine the total Fe (TFeOx) and Mn (TMnOx) contents. Utilising a PerkinElmer Optima 2100 ICP-OES device, the resulting solutions were examined. As proposed by Shuman (1985), iron and manganese (Mn) oxides were also chemically fractionated as total and amorphous. Hydroxilaminhydrochloride also dissolved free Mn oxides (Chao, 1972).

Properties of farmyard manure

Cattle dung that had naturally decomposed was sieved through a 2 mm mesh screen, mixed, and then utilised in the experiment and for analysis. The methods outlined by Kacar (2014) were used to determine the characteristics of the farmyard manure (FYM) given in Table 2.

Waterlogging experiment

Five soils out of 10 samples chosen according to their response to flooding by principal component analysis were employed for the adsorption investigation (Oren, 2023). To examine the relationship between redox potential and organic matter, 200 g of each soil sample were put in plastic containers and incubated under two FYM treatments: application of 4 g FYM/100 g soil and control (no amendment). Three replicates of each treatment were used in the experiment, and samples were immersed in water for 0, 7, 14, 21, and 40 days. Five soils, two manure treatments, five time periods, and three repetitions were used to create 150 experimental units in total. The samples were incubated at 22 ± 3°C in the dark in a 1:2 soil-to-water suspension.

Phosphorus adsorption experiment

For phosphorus adsorption experiments, 2 g of air-dry soil previously incubated, dried in an oven at 40°C and homogenised by grinding were weighed into polypropylene containers and equilibrated at a constant temperature of 20°C for 24 h with 25 mL of 0, 5, 10, 20, 30, or 40 mg P L^{-1} solutions prepared in 0.01 M $CaCl_2$. After equilibration, the suspensions were centrifuged at 3000 rpm for 10 min, and the supernatants were filtered through blue-band filter paper. The phosphorus concentrations in the extracts were determined spectrophotometrically at 880 nm using a Thermo Genesys 10S UV–VIS spectrophotometer according to the modified ascorbic acid method described by Murphy and Riley (1962).

Evaluation of adsorption data

The Freundlich and Langmuir adsorption models were fitted to the experimental data, and regression analysis was used to evaluate the model's appropriateness. Several adaptations of the Langmuir equation have been devised to take into consideration the contributions of P releasing from the added organic materials in the incubated soils (Brock et al., 2007; Zhang et al., 2010; Wang et al., 2014; Wang et al., 2016). In the P-enriched soils, indigenous P concentrations should also be included in the total adsorbed P of the Langmuir equation to describe P adsorption data because the amount of P releasing/desorbing is too large to be ignored (Wang et al., 2022). Both some soil samples and FYM contain large amount of P, abovementioned modification was performed. By this way it can be possible to reduce outlier data points (mainly at lower- or upper-end of the isotherms) and increase the determination coefficient of the regression line. Therefore a modified version of the Langmuir equation was utilised as: $C_e/S_T = Ce/S_{max} + 1/(K_L*S_{max})$

where S_T representing the amount of total P adsorbed per unit soil mass (mg kg^{-1}), which includes both P adsorbed to the soil before adsorption experiments (S_0) and P adsorbed/desorbed from/into the equilibrating solution (S_s), C_e representing the equilibrium concentration of P in solution (mg L^{-1}), and K_L and S_{max} representing the binding energy constant and maximal adsorption capacity, respectively.

Table 1. Physico-chemical properties of the experimental soils

Properties	Units	Sample no				
		1	2	3	4	5
pH		7.7	7.7	7.50	6.8	7.3
EC	µS cm^{-1}	128	212	473	123	377
OM	g kg^{-1}	20.6	17.3	32.5	19.8	69.4
CCE		6.6	15.4	65.7	13.2	232
Sand		675	425	582	293	506
Silt		159	310	164	204	222
Clay		167	265	254	503	272
CEC	cmol kg^{-1}	17.1	21.8	38.2	34.7	36.8
P	mg kg^{-1}	23.1	61.6	216	2.50	368
MnOx		139	152	146	162	78
AMnOx		99	171	3317	68	52
TMnOx		422	459	3652	309	337
AFeOx		2 280	8 441	3 924	2 071	1 247
TFeOx		18 285	19 122	18 017	21 067	14 353

Table 2. Properties of farmyard manure

Parameters	Unit	Results
Moisture	g kg^{-1}	105
OC	g kg^{-1}	330
P total	g kg^{-1}	1.89
P$_{\text{(in water extract, 1/5, W/V)}}$	mg kg^{-1}	67.3

The Freundlich model is commonly stated as $S= K_F C^{1/n}$. The similar abovementioned approach was also applied for the Freundlich model by including the FYM effect and was linearized as follows: $Log (St) = Log K_F + 1/n \log C_e$

where S_T is the total amount of P adsorbed per unit soil mass (mg kg^{-1}), C_e is the equilibrium concentration (mg L^{-1}), and K_F and n are empirical constants.

Results and Discussion

One of the noteworthy results of this study is the high P status of the analyzed soils. Total P concentrations ranged from 528 mg kg^{-1} to 2 246 mg kg^{-1}, indicating substantial P enrichment (Table 1). Such elevated levels are most likely a consequence of long-term intensive agricultural practices in the study area. The Olsen-P contents further support this interpretation, reflecting the legacy of heavy fertilization (Fischer et al., 2017; Couic et al., 2022). This is consistent with the fact that commercial P fertilizers contain large amounts of soluble and readily reactive P (Zhang et al., 2020). The accumulation of both total and plant-available P in these soils is therefore expected to influence their adsorption behaviour, as reflected in the high Freundlich and Langmuir adsorption parameters obtained under different flooding and FYM treatments. Considering the high data set utilization rates and coefficients of determination of Freundlich and Langmuir adsorption isotherms, it can be said that Langmuir adsorption isotherm describes the experimental data relatively better.

Phosphorus availability and partition among various geochemical fractions in calcareous soils is largely governed by adsorption processes, which can be quantitatively described using adsorption isotherms such as the Freundlich and Langmuir models. The present dataset evaluates the effects of flooding duration (0–40 days) and farmyard manure (FYM) amendment (0 and 4 g 100 g^{-1} soil) on P adsorption in five different calcareous soils. Sorption isotherms of the soils were illustrated in Figure 1.

The Freundlich adsorption constant (KF) and the heterogeneity factor (1/n) varied widely across soils and treatments, reflecting both soil type and management effects. KF values generally increased with flooding duration. For example, in S1, KF increased from 51.7 L kg-1 at day 0 to 115.0 L kg-1 at day 40. A similar upward trend was observed in S2 (70.6 → 146.4 L kg-1) and S5 (95.3 → 176.8 L kg-1). In most soils, 1/n values remained in the range of 0.6–0.8, indicating favourable adsorption, though S3 showed higher 1/n (0.8–0.9) suggesting slightly more heterogeneous surfaces or mechanisms. High R^2 values (0.943–0.998) confirmed a good fit of the Freundlich model.

In the FYM treated soils, at day 0, FYM markedly reduced KF values (e.g., S1: 51.7 → 12.0 L kg-1; S2: 70.6 → 9.6 L kg-1; S5: 95.3 → 26.0 L kg-1), likely due to competition from organic ligands or readily available and/or released P from the FYM during the incubation. With flooding progression, KF increased considerably (e.g., Soil 1: 12.0 → 137.0 L kg-1 at day 40; S5: 26.0 → 207.3 L kg-1), suggesting that organic matter decomposition and Fe/Al oxide transformations enhanced P retention. 1/n values under FYM treatment were generally higher at day 0 (>1.0), implying less favourable adsorption and readily available P in the FYM, but declined with time to levels closer to untreated soils.

Langmuir constants (KL and Smax) provide insights into binding energy and maximum adsorption capacity, respectively. The KL values of the original soils had soil dependent fluctuation but generally increased with flooding. For example, in S1, KL rose from 1.133 (day 0) to 2.167 (day 21), followed by a sharp decline at day 40 (0.210), indicating possible desorption or saturation effects. Smax values consistently increased with flooding. In S2, Smax rose from 1326 mg kg^{-1} (day 0) to 1527 mg kg^{-1} (day 40). S3 and S5 showed particularly high Smax values (>1900 and >2700 mg kg^{-1}, respectively).

KL values of FYM treated soils were very low at day 0 (e.g., S2: 0.212; S4: 0.311), but increased with flooding, indicating initially weak P binding that strengthened over time. Smax was markedly enhanced by FYM, especially in S2, S3, and S5. For example, S5 recorded Smax values exceeding 2800 mg kg^{-1} under FYM compared to ~2700 mg kg^{-1} without FYM. This suggests that FYM not only increased adsorption capacity but also stabilized P binding with prolonged flooding. High R^2 (>0.981) confirmed excellent fits of the Langmuir model owing to the inclusion of indigenous soil P and FYM-P contents. The isotherms determination coefficients were highly weak (below 0.5) to satisfactorily describe the sorption data without performing the modification. This manner was exaggerated by very high total and plant available P concentration and FYM incorporation at shorter waterlogging period.

In all soils, flooding promoted P adsorption capacity (higher KF and Smax), reflecting increased reactive surface sites due to redox-induced mineral transformations. FYM initially reduced adsorption strength (low KF, KL), but with time under flooding, it enhanced both adsorption intensity and capacity, likely through complexation and formation of stable organo-mineral associations and post-submerge secondary oxide precipitates. S3 and S5 exhibited the highest Smax values, while S4 showed strong KL responses, indicating soil-specific mineralogical controls on P dynamics.

The combined effects of flooding and FYM application strongly influenced phosphorus adsorption behaviour in calcareous soils. Flooding consistently enhanced adsorption capacity, while FYM initially suppressed but later promoted stronger and higher-capacity adsorption systems. These findings highlight the interactive role of organic matter and redox dynamics in regulating P availability in calcareous agro-ecosystems.

Table 3. Phosphorus adsorption isotherm parameters of the experimental soils

Soil	**FYM**	**Flooding**	**Freundlich**			**Langmuir**		
No	**(g 100 g^{-1})**	**(Days)**	**K_F (L kg^{-1})**	**$1/n$**	**R^2**	**K_L**	**S_{max}* (mg kg^{-1})**	**R^2**
1	0	0	51.7	0.647	0.970	1.133	1 176	0.989
1	0	7	69.0	0.603	0.985	1.474	1 190	0.992
1	0	14	79.5	0.694	0.998	1.569	1 250	0.994
1	0	21	108.9	0.644	0.996	2.167	1 282	0.996
1	0	40	115.0	0.674	0.986	0.210	690	0.993
1	4	0	12.0	1.230	0.996	0.395	1 300	0.990
1	4	7	107.5	0.585	0.990	1.233	1 323	0.996
1	4	14	119.2	0.641	0.989	1.322	1 376	0.996
1	4	21	136.5	0.589	0.970	1.409	1 383	0.991
1	4	40	137.0	0.593	0.985	1.582	1 368	0.998
2	0	0	70.6	0.617	0.989	2.762	1 326	0.999
2	0	7	85.2	0.642	0.989	1.972	1 445	0.993
2	0	14	103.5	0.672	0.993	2.282	1 490	0.996
2	0	21	135.9	0.635	0.991	3.051	1 511	0.997
2	0	40	146.4	0.677	0.973	3.376	1 527	0.997
2	4	0	9.6	1.406	0.987	0.212	1 866	0.994
2	4	7	91.1	0.670	0.994	1.284	1 701	0.995
2	4	14	119.7	0.671	0.996	1.297	1 626	0.996
2	4	21	132.1	0.604	0.996	1.416	1 605	0.997
2	4	40	120.8	0.704	0.993	1.471	1 626	0.998
3	0	0	34.8	0.800	0.986	3.699	1 733	0.999
3	0	7	59.4	0.824	0.995	4.389	1 808	0.998
3	0	14	80.6	0.787	0.994	3.250	1 923	0.998
3	0	21	73.7	0.887	0.997	3.335	1 934	0.997
3	0	40	90.9	0.785	0.996	3.615	1 934	0.998
3	4	0	11.6	1.199	0.998	0.685	1 919	0.999
3	4	7	75.7	0.866	0.997	1.740	2 045	0.996
3	4	14	96.6	0.780	0.995	1.968	2 049	0.998
3	4	21	88.9	0.823	0.996	1.972	2 045	0.997
3	4	40	68.8	0.946	0.989	1.641	2 066	0.997
4	0	0	114.0	0.545	0.992	3.806	847	0.997
4	0	7	174.0	0.563	0.995	4.292	971	0.994
4	0	14	179.4	0.629	0.986	4.040	990	0.995
4	0	21	213.5	0.611	0.992	5.000	1 000	0.993
4	0	40	221.2	0.628	0.945	4.950	1 010	0.997
4	4	0	10.6	1.656	0.976	0.311	1 181	0.981
4	4	7	172.0	0.588	0.943	1.981	1 063	0.993
4	4	14	144.1	0.878	0.988	1.539	1 144	0.990
4	4	21	198.9	0.571	0.998	1.870	1 107	0.994
4	4	40	241.9	0.512	0.991	2.298	1 119	0.998
5	0	0	95.3	0.645	0.998	12.188	2 564	1
5	0	7	150.8	0.626	0.998	12.032	2 681	0.999
5	0	14	165.5	0.675	0.998	13.250	2 695	0.999
5	0	21	168.9	0.635	0.993	15.542	2 681	0.999
5	0	40	176.8	0.696	0.987	13.667	2 710	0.999
5	4	0	26.0	1.214	0.991	1.439	2 825	0.998
5	4	7	156.0	0.703	0.976	5.950	2 801	0.999
5	4	14	176.8	0.640	0.996	6.755	2 793	0.999
5	4	21	127.5	0.783	0.992	4.450	2 809	0.999
5	4	40	207.3	0.546	0.995	6.865	2 801	0.999

*S_{max} : Maximum adsorpsiyon

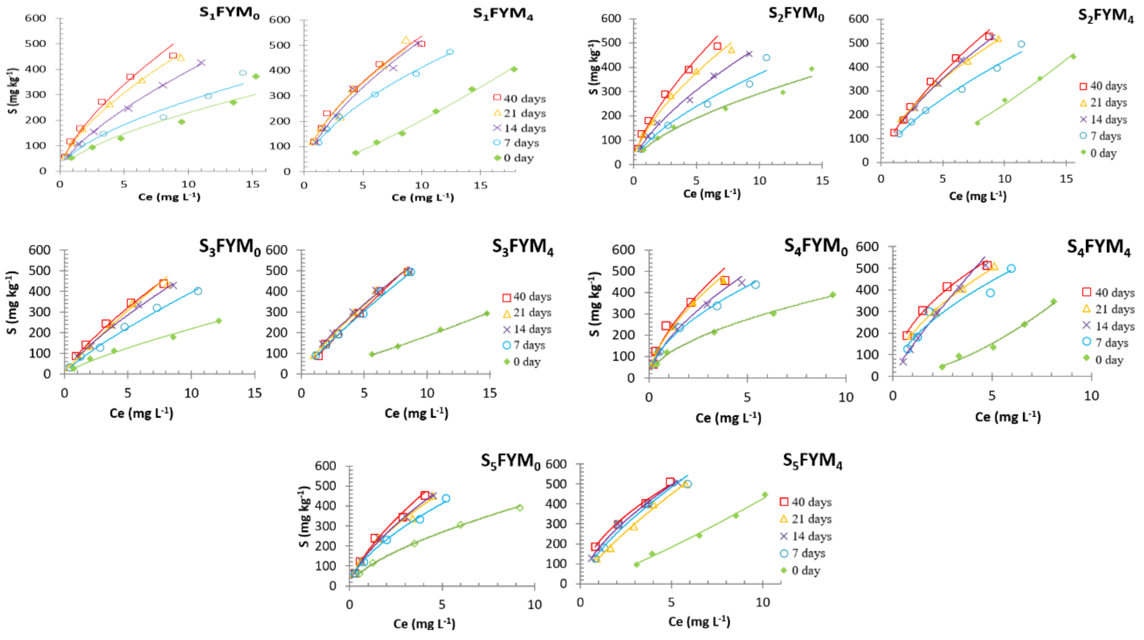

Figure 1. The effect of waterlogging duration on the sorption isotherms of experimental soils (S1-S5) with and without farmyard manure treatments

Ions like Fe and Al (Agbenin, 2003; Yan et al., 2013) and Ca (Pizzeghello et al., 2011, 2014) play major role in controlling the sorption and/or precipitation of P in soils as a function of soil pH and the amounts of ions in question (Lindsay, 2001; Uygur, 2009). Amorphous Fe and Al oxyhydroxides were found to be essential in controlling P sorption in the paddy/waterlogged soils (Yan et al., 2017). Similarly, Campos et al. (2016) investigated a set of tropical soils with S_{max} ranging from 60 to 5500 mg kg^{-1}, and found that Al and Fe were critical ions in controlling P sorption in these soils. However, Ca ions or carbonate content has detrimental functions in the adsorption, solubility and partition of calcareous soils of arid-semiarid regions (Uygur, 2009; Mahdi et al., 2023). As the calcareous soil exposed to flooding the chemistry of the equilibrium solution, mineralogy of the oxides of Fe and Mn are to change considerably (Amrutha et al., 2021; Ymeti et al., 2019) along with the surface properties. The dissolution of Fe and Mn oxides upon flooding results in the precipitation of amorphous oxyhydroxides in the subsequent drying period. These newly formed amorphous components have very high structural discrepancies that enhance sorption sites for P. As a matter of fact, Couic et al. (2022) reported in their studies that the adsorption ability of FeOx decreases with aging and increasing crystallization. Similarly (Adhami et al. (2012) reported that the accumulation of P associated with free and crystalline Fe and Al oxides was promoted by long-term waterlogging incubation period where as less anoxic conditions at field capacity oxalate- citrate-, and citrate-ascorbate-extractable Fe and Al and free manganese oxides have the main control over P. This suggest the more dissolution of Fe, Al and Mn during the anoxic conditions can result in the more amorphous oxides of Fe, Al, and Mn that scavenge P from the solution.

S_{max} was found to be negatively correlated with SOM (Daly et al., 2001) and low molecular weight organic acids that evolved during the decomposition of fresh organic matter (Moradi et al., 2012; Oral and Uygur, 2018). This was especially true for soils with high SOM contents, like over 40%, where the magnitude of organic anions from SOM decomposition can compete for P sorption sites. Some researches, however, shown a favourable correlation between S_{max} and SOM (Kang et al., 2009; Campos et al., 2016). Because organic matter can form stable complexes with Al and Fe, it can hinder their crystallisation in soil that is rich in both elements. This can enhance P sorption as the amount of noncrystalline Al and Fe grows (Borggaard et al., 1990; Kang et al., 2009). The other point regarding the organic matter is that C:N ratio which determines the microbial activity, soluble forms of P in the soil. Bouray et al (2024) reported that plant available P concentration of calcareous soils is detrimentally affected by C:N ratio with a *r* value of -0.98. It is well-known that fresh organic matter incorporation into waterlogging soils boosts the redox reactions of Fe and Mn. Therefore, FYM addition caused similar effect and with the longer flooding duration the larger amounts of Fe and Mn dissolved. As the soils were subjected a quick drying process at 40°C in the oven, all of the soluble forms precipitated as amorphous oxyhydroxides. The other point is that the oxide minerals occur either free or coatings on the other soil components (Uygur and Rimmer, 2000). This occurrence may cover the surface of clay and carbonate minerals (Uygur, 2009). Clay minerals has very high ability to adsorb P (Bouray et al., 2024; Szogi et al., 2024) and carbonates buffer Ca and pH in soil solution (Wang et al., 2015) despite their relatively lower P adsorption (Ren et al., 2021). Both of these mechanisms in fact can contribute a larger S_{max}. In addition, reducing conditions may dissolve Fe/Mn oxides on carbonates surfaces to condition larger amount of surface precipitation of P. An NMR study shows that calcite, which is typical mineral of calcareous soils, scavenge P as surface precipitations in the form of amorphous calcium phosphate (ACP) as short as 30 min, then upon ageing the ACP transformed to carbonated hydroxyapatite at lower concentration and to OCP, later to brushite, and eventually to carbonated hydroxyapatite at higher loadings (Wang et al., 2023).

In addition, stronger interaction between Al and SOM may occur in the waterlogged soils than that between Fe and SOM, because the former showed a more significant relationship (Yan et al., 2013; Yan et al., 2015). We assume that waterlogged soils treated with FYM had greater P sorption than those solely waterlogged soils (Fig. 1) partly due to the FYM treatment enriched SOM contents and amorphous Fe oxides.

In some cases, the addition of FYM to submerged soils results in a decrease in the adsorption isotherm. This phenomenon was observed in S2. In this particular soil, the maximum adsorption, initially measured at 1 866 mg kg^{-1}, was found to have decreased to 1605 mg kg^{-1} over a 21-day period. This can be attributed to two key potential functions of organic matter. First, organic matter has the ability to retain the material added to the system. Second, under high pH conditions, the ionized organic matter in the system tends to form chelates (Gökmen and Uygur, 2022). Indeed, when soil pH decreases, the adsorptive property of organic matter increases (Yan, 2020), whereas at higher pH levels, ionization can lead to chelation and the inhibition of adsorption (Hayatu et al., 2023).

In general, the differences observed in phosphorus adsorption mechanisms can be explained by (i) soil mineral composition which determines the phosphorus adsorption characteristics of the soil, (ii) land use history and the impact of intensive agriculture (Medinski et al., 2018), (iii) variable phosphorus inputs, and iv) treatment induced changes on the surface charges and in the equilibrium solution.

Conclusions

This study demonstrated that both flooding duration and farmyard manure (FYM) application significantly affect phosphorus (P) adsorption behaviour in calcareous soils. While flooding generally enhanced P adsorption capacity (increased KF and S_{max}), FYM initially reduced adsorption due to competition from organic ligands and released P, but with prolonged flooding, it led to stronger and more stable adsorption systems. This shift was attributed to redox-induced dissolution and re-precipitation of Fe/Mn oxides as amorphous phases, which provided additional sorption sites.

Langmuir and Freundlich isotherms successfully described P adsorption, with the modified Langmuir model offering better fit due to consideration of indigenous and added P. Soil-specific properties such as carbonate content, clay, and oxide mineralogy played key roles in determining adsorption behaviour. Particularly in soils with high organic matter, longer flooding promoted the formation of organo-mineral complexes and increased S_{max}.

Overall, the interaction between waterlogging and organic amendments must be carefully managed in calcareous soils to balance P availability and environmental risks. These findings are especially relevant under changing climate conditions that may increase flooding frequency and necessitate organic matter use in sustainable agriculture. Additionally, the results are also important for understanding the changes in P availability and fertilization requirement in soils that become saturated with water at different intervals following the rainy season. Despite an increased adsorption, a drying period can limit the mobility of P in calcareous soils; waterlogging duration, along with FYM treatments, can stimulate P mobility, posing environmental risks such as leaching and eutrophication of surface waters.

Acknowledgement

The authors gratefully acknowledge the financial support provided by the Scientific Project Foundation Unit of Isparta University of Applied Sciences, Türkiye (2021-Dl-0149).

Author Contributions

The authors are equally contributed to all parts of the manuscript

Conflict of Interest

The authors declare that they have no conflict of interest.

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