The Effectiveness of Humus Acids from Different Sources in Improving Phosphorus Availability in Soils with Varying Gypsum Content

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Abstract

This study evaluated the effectiveness of humic substances extracted from cow manure and date palm fronds in improving phosphorus availability in two soils with different gypsum contents. The soils contained 98 and 445 g kg^{-1} gypsum and were designated S1 and S2, respectively. Total humic substances, humic acid, and fulvic acid were applied at 0, 20, 40, and 60 L ha^{-1}, together with phosphorus supplied as triple superphosphate at 0, 50, and 100 mg P kg^{-1}. An experiment was conducted between October 2025 and March 2026 using a completely randomized design (CRD) consisting of three replications and 144 treatments in total. Soil samples were incubated at 25 ± 1 °C for 30 days while moisture was maintained at 60-80% field capacity, and available phosphorus was subsequently determined. Phosphorus availability was consistently lower in S2 than in S1 and increased with extract application rate. Total humic substances generally produced higher available phosphorus than the separated humic and fulvic acid fractions. Without mineral phosphorus addition, mean available phosphorus was 5.596 and 4.944 mg kg^{-1} for cow-manure extracts in S1 and S2, compared with 5.390 and 4.708 mg kg^{-1} for palm-frond extracts. At 100 mg P kg^{-1}, the corresponding means were 13.066 and 10.073 mg kg^{-1} for cow manure and 12.004 and 9.753 mg kg^{-1} for palm fronds. The highest reported concentration, 18.073 mg kg^{-1}, occurred in S1 receiving total cow-manure humic substances at 60 L ha^{-1} and 100 mg P kg^{-1}. These findings support the combined use of organic extracts and mineral phosphorus to improve phosphorus availability in gypsiferous soils. Further testing is required to establish field application rates and agronomic optima.

Keywords: cow manure; palm fronds; calcium complexation; incubation; organic amendments

Introduction

Gypsiferous soils occur widely in arid and semi-arid regions of Iraq [12]. This soil is used in various agricultural sectors, including grain cultivation; however, Iraq's productivity per unit area remains low compared to global production [12]. One of the main reasons for the decrease in productivity is the decrease in phosphorus availability as a result of its fixation due to the high degree of reaction of the soil and the high content of calcium carbonate, which is the source of calcium ions in the soil solution [21]. Calcium reacts with phosphorus to form poorly soluble compounds such as calcium phosphate, and plants growing in this soil can only use a small proportion, ranging from 25% to 30%, of the added fertilizer [8, 9].

Therefore, the presence of gypsum in the soil may be an important factor limiting the movement and absorption of phosphorus by plants, especially in alkaline and semi-arid conditions [1]. Although this soil contains a sufficient amount of total phosphorus, its availability is low, not exceeding 0.1% of total phosphorus [18]. A study examining the forms of phosphorus in the soil, particularly mineral phosphorus and determining its proportions, as it represents the form that affects plant growth and productivity, revealed that calcium phosphorus constitutes the majority of mineral phosphorus in gypsum soil [24]. While the use of phosphorus fertilizers can compensate for a lack of phosphorus in the soil, its effectiveness depends on its ability to reduce the addition of calcium from the fertilizer [38]. Several recent studies have indicated that humic substances are among the most important determinants of soil productivity, due to their multiple effects, including the release of nutrients to plants, improvement of the physical and biological properties of soil, and increased fertilizer effectiveness [28] and [20]. The complex interactions between gypsum, phosphorus, and organic carbon in gypsum soil management require regulating calcium ion restriction, adding organic matter, and controlling soil pH to enhance phosphorus availability. Furthermore, it is known that organic matter and phosphate-solubilizing microorganisms improve phosphorus availability in gypsum soils through processes including organic acid production [32] and by acting as chelating agents, such as chelating calcium in the soil solution, thanks to active groups such as phenols and carboxyl groups that increase phosphorus availability [32]. Fulvic and humic acids are the basic components of organic matter. These acids are usually formed during the decomposition of plant or animal remains into humus, and are broken down by microorganisms [34]. Generally, In addition to its resistance to degradation, it is composed of a mixture of aromatic and aliphatic compounds. The comparison between humic acid and fulvic acid is based on the optical density ratio (E 600/400), molecular weight, oxygen-to-hydrogen-to-carbon ratio, and the presence of aliphatic and aromatic groups [7]. Differences in structure significantly affect their behavior, activity, phosphorus release efficiency, and mobility at equilibrium, through the formation of humic phosphate compounds that lead to increased phosphorus release [16]. The active groups (HCOO-, OH-, COO-) in humic acids form complexes with positive ions such as calcium [26], which reduces the formation of calcium phosphate. This also contributes to reducing competition for adsorption sites on the surface of carbonate minerals, which increases their availability in the equilibrium medium, due to a decrease in binding energy, and thus an increase in phosphorus release. Aswad et al [2] and Hamid et al. [14] indicate that the concentration of phosphorus increases with increasing levels of humus acids (humic and fulvic) acids released from organic matter. This study compares the levels and types of humic material sources and their effect on phosphorus availability in two types of soil with varying gypsum content.

Studies in Iraq have demonstrated improved phosphorus availability after combining phosphate rock with organic materials [22], and altered crop phosphorus nutrition after blending triple superphosphate with urea [13]. Organic fertilizer type also affected phosphorus release from rock phosphate [23], while a potato field study reported improved soil nutrient availability under combined humic acid and foliar treatments [31].

Material and Methods

Acid extraction

Humus acids (humic substances, humic acid, and fulvic acid) were investigated from organic sources (cow dung and date palm manure) using sodium hydroxide (0.1 mol L^{-1}), following the extraction procedure described in Page et al. [27]. The humic material was shaken for 16 h at a speed of 400 rpm with sodium hydroxide at a concentration of 0.1 mol/L (1/20 w/v). The humin was then separated, leaving the extract which represented the humic substances (humic acid and fulvic acid). The extract was then placed in plastic bottles for storage. The humic acid and fulvic acid were then separated by centrifugation for 30 minutes at 12,000 rpm. The supernatant was carefully collected, filtered through a 0.45 µm membrane, and the pH was adjusted to 2 using 1 mol L^{-1} hydrochloric acid. The resulting solution was left to stand at 24 °C and then centrifuged as previously described. Fulvic acid was extracted directly, while humic acid was extracted by washing it twice with deionized water and dissolving it in a sodium hydroxide solution at a concentration of 0.01 mol L^{-1}. Deionized water was added to the humic and fulvic acid solutions until the total volume reached 1 L. The final pH was 7.8 using humic acid and 3.7 using fulvic acid.

Analysis of soil

Two soil samples were taken from the topsoil layer (0–0.3)m, exhibiting a wide range of gypsum content. The soil samples underwent chemical and physical property analysis, including air drying, grinding, and sieving through a 2 mm sieve, followed by various chemical analyses (Table 1). A 1:1 soil-to-water ratio was used to measure soil pH and electrical conductivity [19]. Dissolved cations (Ca^{2+}, Mg^{2+}, Na^{2+}, K^{+}) and anions (HCO_3^{2-}, CO_3^{2-}, Cl^{-}, SO_4^{2-}) were determined using standard methods [27]. Cation exchange capacity (CEC) was determined using the ammonium acetate extraction method (1 M NH_4 OAC) [29]. Using Kjeldahl's digestion method, we measured the total amount of nitrogen in the samples [5]. To determine the amount of available phosphorus in the soil, it was extracted using a 0.5 M sodium bicarbonate (NaHCO3) solution at pH 8.5 [25]. Following the procedure of Day [10], the particle size distribution was measured using a densitometry method. The organic matter content of the samples was determined using the method described in [35]. Calcium carbonate equivalents were determined using a calcium densitometry method and 1 M hydrochloric acid (HCl) according to [11]. Gypsum content was determined using the method according to Richards [30].

Incubation experiment

The experiment was conducted from October 2025 to March 2026 using a completely randomized design (CRD) with three replicates and a total of 144 treatments for the entire experiment. Two soils differing in gypsum content were studied: S1 (98 g kg^{-1}) and S2 (445 g kg^{-1}). The extracts were obtained from cow manure and date palm fronds and comprised total humic substances (HS; T1), humic acid (HA; T2), and fulvic acid (FA; T3). Extract application levels were 0 (control), 20 (L1), 40 (L2), and 60 (L3) L ha^{-1}. Mineral phosphorus levels were 0, 50, and 100 mg P kg^{-1}, supplied as triple superphosphate (TSP). Each incubation container held 100 g of air-dried soil passed through a 2 mm sieve. The treated soil was incubated at 25 ± 1 °C for 30 d, and moisture was maintained at 60-80% field capacity by weighing the containers and replenishing water losses. After incubation, a 30 g soil subsample was collected from each container, air-dried, and analyzed for available phosphorus.

Table 1. Some chemical and physical characteristics of the studied soils.

S2	S1	Unit	Property
7.65	7.32	--	pH
2.34	2.51	dS m^{-1}	EC
445	98	g kg^{-1}	CaSO4.2H2O
203	243	g kg^{-1}	CaCO3
9.75	11.04	g kg^{-1}	O.M
11.82	14.17	cmolc kg^{-1}	CEC
668	563	g kg^{-1}	Sand
145	240	g kg^{-1}	Silt
187	197	g kg^{-1}	Clay
Sandy loam	Sandy loam		Texture
			Available ions
13.5	21.1	mg kg^{-1}	N
3.89	4.21	mg kg^{-1}	P
97.76	128.54	mg kg^{-1}	K
			Soluble ions
2.15	1.32	mmol L^{-1}	Na
12.91	5.30	mmol L^{-1}	Ca
3.26	6.77	mmol L^{-1}	Mg
1.60	2.73	mmol L^{-1}	Cl
Nil	Nil	mmol L^{-1}	CO3
2.68	1.26	mmol L^{-1}	HCO3
15.97	9.55	mmol L^{-1}	SO4

S1 and S2 contain 98 and 445 g kg^{-1} gypsum, respectively. EC, electrical conductivity; O.M., organic matter; CEC, cation exchange capacity.

Result

Table 2 presents the effects of cow-manure extract type and application level on available phosphorus without mineral phosphorus addition.

Table 2 shows a significant decrease in phosphorus availability with increasing gypsum content in the soil. The average availability in treatment S1 was 5.596 mg kg^{-1}, while in treatment S2 it was 4.944 mg kg^{-1}. A significant difference can also be observed in the types of acids used in the table, with the treatments arranged in the following sequence: T1 – T2 – T3, resulting in averages of 5.474, 5.173, and 5.166 mg kg^{-1} respectively. Furthermore, the table shows a direct relationship between available phosphorus and acid utilization levels, with the average availability in treatment L3 being 6.096 mg kg^{-1}, while in the control treatment it was 4.053 mg kg^{-1}. As shown in the previous table, significant differences were found in the interactions between the gypsum content in the soil and the type of acid. In treatment S1, the application order was S1T1, then S1T2, then S1T3, with averages of 5.845, 5.543, and 5.404 mg kg^{-1}, respectively. In treatment S2, the order was S2T1, then S2T3, then S2T2, with averages of 5.103, 4.928, and 4.802 mg kg^{-1}, respectively. According to the same table, the interaction between soil gypsum content and acid application levels showed a significant benefit for treatment S1L3, which achieved the highest average dose of 6.426 mg kg^{-1}, A lower average dose of 4.213 mg kg1 was observed in the control group. Compared to the control group, treatment S2L3 recorded the highest average dose of 5.766 mg kg1, while treatment S2L3 recorded the lowest average dose of 3.893 mg kg1. Furthermore, the table shows a significant interaction between the type of acid and its level of use, with the T1L3 treatment group receiving a dose of 6.468 mg kg^{-1}, and the average dose in the control treatment being 4.053 mg kg^{-1}. The table also indicates no statistically significant interaction between soil gypsum content, acidity, and extract application levels when triple superphosphate (0 mg P kg^{-1}) is not used.

Table 2. Available phosphorus (mg kg⁻ ¹) as affected by cow manure extract type and application level at 0 mg P kg⁻ ¹.

Mean	L3	L2	L1	Control	Extract	Soil
5.845	6.837	6.43	5.9	4.213	T1	S1
5.543	6.31	6.093	5.547	4.213	T2	S1
5.404	6.12	6.027	5.257	4.213	T3	S1
5.103	6.1	5.573	4.843	3.893	T1	S2
4.802	5.487	5.263	4.563	3.893	T2	S2
4.928	5.71	5.473	4.633	3.893	T3	S2
5.596	6.426	6.183	5.568	4.213	Mean	S1
4.944	5.766	5.437	4.68	3.893	Mean	S2
5.474	6.468	6.002	5.372	4.053	T1	Mean
5.173	5.903	5.678	5.055	4.053	T2	Mean
5.166	5.915	5.75	4.945	4.053	T3	Mean
—	6.096	5.81	5.124	4.053	L	Mean

LSD at 5%: S×T×L = N.S; T×L = 0.1858; S×L = 0.1517; S×T = 0.1314; L = 0.1073; T = 0.0929; S = 0.0759

S1 = 98 and S2 = 445 g kg⁻ ¹ gypsum; T1 = total humic substances, T2 = humic acid, T3 = fulvic acid; control = 0, L1 = 20, L2 = 40, L3 = 60 L ha⁻ ¹. LSD = least significant difference; NS = not significant.

Table 3 shows a significant decrease in available phosphorus with increasing gypsum content in the soil, with treatment S1 recording the highest average of 5.390 mg kg⁻ ¹, while treatment S2 recorded the lowest average of 4.708 mg kg⁻ ¹.

Based on the table above, there are significant differences in the types of acids used. The treatments were arranged in the following sequence: T1 – T3 – T2, with averages of 5.219, 5.026, and 4.902 mg kg⁻ ¹, respectively. As shown in the table, there is a direct relationship between the amount of available phosphorus and the levels of acid application. The highest average phosphorus in treatment L3 was 5.533 mg kg⁻ ¹, while the average in the control treatment was 4.053 mg kg⁻ ¹. Using the table, significant differences were found in the interactions between soil gypsum content and acid type. In treatment S1, the order of treatment was S1T1, then S1T2, then S1T3, with averages of 5.530, 5.366, and 5.273 mg kg⁻ ¹, respectively. In treatment S2, the order was S2T1, then S2T3, then S2T2, with averages of 4.908, 4.778, and 4.438 mg kg⁻ ¹, respectively. The same table illustrates the interaction between soil gypsum content and acid application levels. Treatment S1L3 showed a marked advantage, achieving the highest average at 5.931 mg kg⁻ ¹, while the control treatment recorded the lowest average at 4.213 mg kg⁻ ¹. In contrast, treatment S2L3 recorded the highest average at 5.134 mg kg⁻ ¹, while the control treatment recorded the lowest average at 3.893 mg kg⁻ ¹. The table above shows a comparison between the average T1L3 treatment of 5.833 mg kg⁻ ¹ and the average control treatment of 4.053 mg kg⁻ ¹. Furthermore, the table indicates that there is no statistically significant interaction between soil gypsum content, acidity type, and application levels when triple superphosphate fertilizer is not used.

Table 3. Available phosphorus (mg kg⁻ ¹) as affected by palm fronds extract type and application level at 0 mg P kg⁻ ¹.

Mean	L3	L2	L1	Control	Extract	Soil
5.530	6.193	6.070	5.643	4.213	T1	S1
5.366	5.947	5.803	5.500	4.213	T2	S1
5.273	5.653	5.753	5.473	4.213	T3	S1
4.908	5.473	5.367	4.900	3.893	T1	S2
4.438	4.693	4.650	4.513	3.893	T2	S2
4.778	5.237	5.140	4.843	3.893	T3	S2
5.390	5.931	5.876	5.539	4.213	Mean	S1
4.708	5.134	5.052	4.752	3.893	Mean	S2
5.219	5.833	5.718	5.272	4.053	T1	Mean
4.902	5.32	5.227	5.007	4.053	T2	Mean
5.026	5.445	5.447	5.158	4.053	T3	Mean
—	5.533	5.464	5.146	4.053	L	Mean

LSD at 5%: S×T×L = NS; T×L = 0.1996; S×L = 0.163; S×T = 0.1411; L = 0.1152; T = 0.0998; S = 0.0815

S1 = 98 and S2 = 445 g kg⁻ ¹ gypsum; T1 = total humic substances, T2 = humic acid, T3 = fulvic acid; control = 0, L1 = 20, L2 = 40, L3 = 60 L ha⁻ ¹. LSD = least significant difference; NS = not significant.

Table 4 shows that with increasing gypsum content, the availability of phosphorus decreased significantly, and treatment S1 achieved the highest average availability of 10.426 mg kg⁻ ¹, while treatment S2 achieved an average of 7.77 mg kg⁻ ¹. The statistical analysis also revealed significant differences between the types of acids used, which were ranked sequentially as follows: T1, T2, and T3, achieving averages of 9.768, 8.804, and 8.721 mg kg⁻ ¹ respectively.

The same table indicates a direct correlation between phosphorus abundance and the level of addition, with treatment L3 achieving the highest average abundance of 10.726 mg kg⁻ ¹, while the control treatment achieved an average of 6.755 mg kg⁻ ¹. As shown in the previous table, significant differences were found in the interaction between the gypsum content and the type of acid. In treatment S1, the order of concentrations was as follows: S1T1, then S1T2, then S1T3, with average concentrations of 11.173, 10.321, and 9.783 mg kg⁻ ¹, respectively. In treatment S2, the order was as follows: S2T1, then S2T3, then S2T2, with average concentrations of 8.363, 7.659, and 7.287 mg kg⁻ ¹, respectively. Furthermore, the same table compares the mean treatment T1L3 12.025 mg kg⁻ ¹ with the mean control treatment 6.755 mg kg⁻ ¹, indicating a statistically significant interaction between the type of acid and its application level. The table above shows a weak but statistically significant effect resulting from the three-way interaction between soil gypsum content, acidity type, and application level. In treatment S1, treatment S1T1L3 achieved the highest available phosphorus concentration of 13.437 mg kg⁻ ¹, while the control treatment recorded the lowest available phosphorus concentration of 7.910 mg kg⁻ ¹. Conversely, in treatment S2, treatment S2T1L3 achieved the highest available phosphorus concentration of 10.613 mg kg⁻ ¹, while the control treatment recorded the lowest available phosphorus concentration of 5.600 mg kg⁻ ¹.

Table 4. Available phosphorus (mg kg⁻ ¹) as affected by cow manure extract type and application level at 50 mg P kg⁻ ¹.

Mean	L3	L2	L1	Control	Extract	Soil
11.173	13.437	12.54	10.807	7.910	T1	S1
10.321	11.877	11.217	10.280	7.910	T2	S1
9.783	10.877	10.523	9.823	7.910	T3	S1
8.363	10.613	9.540	7.700	5.600	T1	S2
7.287	8.547	7.927	7.073	5.600	T2	S2
7.659	9.003	8.587	7.447	5.600	T3	S2
10.426	12.063	11.427	10.303	7.910	Mean	S1
7.770	9.388	8.684	7.407	5.600	Mean	S2
9.768	12.025	11.04	9.253	6.755	T1	Mean
8.804	10.212	9.572	8.677	6.755	T2	Mean
8.721	9.94	9.555	8.635	6.755	T3	Mean
—	10.726	10.056	8.855	6.755	L	Mean

LSD at 5%: S×T×L = 0.3532; T×L = 0.2497; S×L = 0.2039; S×T = 0.1766; L = 0.1442; T = 0.1249; S = 0.102

S1 = 98 and S2 = 445 g kg⁻ ¹ gypsum; T1 = total humic substances, T2 = humic acid, T3 = fulvic acid; control = 0, L1 = 20, L2 = 40, L3 = 60 L ha⁻ ¹. LSD = least significant difference; NS = not significant.

Table 5 shows the extent of phosphorus availability with increasing gypsum content, where treatment S1 achieved the highest average phosphorus availability at 9.427 mg kg⁻ ¹, while treatment S2 recorded the lowest average at 6.939 mg kg⁻ ¹.

The table above shows significant differences between the types of acids used, and the treatments were arranged as follows: T1, T3 and T2, resulting in averages of 8.568, 8.020 and 7.962 mg kg⁻ ¹ respectively. The same table also reveals a direct relationship between the amount of available phosphorus and the amount of acid used, where the control treatment achieved the lowest average phosphorus availability of 6.755 mg kg⁻ ¹, while the L3 treatment achieved the highest average of 9.500 mg kg⁻ ¹. The table above shows significant differences between soil type and acid type used. In treatment S1, the average acid concentration in treatment sequences S1T1, S1T2, and S1T3 was 9.922, 9.303, and 9.056 mg kg⁻ ¹, respectively. In treatment S2, the average acid concentration in treatment sequences S2T1, S2T3, and S2T2 was 7.213, 6.983, and 6.622 mg kg⁻ ¹, respectively. Using the same table, the interaction between soil gypsum content and acid application levels showed a significant advantage for treatment S1L3, which achieved the highest average at 10.866 mg kg⁻ ¹, Approximately 7.910 mg kg1 was recorded as the lowest average in the control treatment. In contrast, treatment S2L3 recorded the highest average at 8.100 mg kg⁻ ¹, while the control treatment recorded the lowest average at 5.600 mg kg⁻ ¹. Furthermore, the table above shows a comparison between the average T1L3 treatment dose of 10.000 mg kg⁻ ¹ and the average control treatment dose of 6.755 mg kg⁻ ¹. According to the same table, the three-way interaction between soil gypsum content, acid type, and acid application level. In treatment S1, treatment S1T1L3 achieved the highest average concentration of 11.913 mg kg⁻ ¹, while the control treatment showed the lowest average concentration of 7.910 mg kg⁻ ¹. Conversely, in treatment S2, treatment S2T1L3 achieved the highest average concentration of 8.657 mg kg⁻ ¹, while the control treatment showed the lowest average concentration of 5.600 mg kg⁻ ¹.

Table 5. Available phosphorus (mg kg⁻ ¹) as affected by palm fronds extract type and application level at 50 mg P kg⁻ ¹.

Mean	L3	L2	L1	Control	Extract	Soil
9.922	11.913	10.563	9.303	7.910	T1	S1
9.303	10.680	9.887	8.733	7.910	T2	S1
9.056	10.003	9.690	8.620	7.910	T3	S1
7.213	8.657	7.770	6.823	5.600	T1	S2
6.622	7.657	7.043	6.290	5.600	T2	S2
6.983	8.233	7.530	6.570	5.600	T3	S2
9.427	10.866	10.047	8.886	7.910	Mean	S1
6.939	8.100	7.448	6.561	5.600	Mean	S2
8.568	10	9.167	8.063	6.755	T1	Mean
7.962	9.1	8.465	7.512	6.755	T2	Mean
8.020	9.1	8.61	7.595	6.755	T3	Mean
—	9.5	8.747	7.723	6.755	L	Mean

LSD at 5%: S×T×L = 0.2686; T×L = 0.1899; S×L = 0.1551; S×T = 0.1343; L = 0.1096; T = 0.095; S = 0.0775

S1 = 98 and S2 = 445 g kg⁻ ¹ gypsum; T1 = total humic substances, T2 = humic acid, T3 = fulvic acid; control = 0, L1 = 20, L2 = 40, L3 = 60 L ha⁻ ¹. LSD = least significant difference; NS = not significant.

Table 6 shows that with increasing gypsum content, available phosphorus decreased significantly. Treatment S1 achieved the highest average at 13.066 mg kg⁻ ¹, while treatment S2 achieved the lowest average at 10.073 mg kg⁻ ¹.

Significant differences were found between the types of treatments shown in Table 6, where the treatments were arranged sequentially as T1-T2-T3, with averages of 12.682, 11.053 and 10.974 mg kg⁻ ¹ respectively. As shown in the table above, there is a direct relationship between available phosphorus and acid utilization levels. The mean for the control treatment was 8.378 mg kg⁻ ¹, while the highest mean for the L3 treatment was 13.586 mg kg⁻ ¹. In the table above, significant differences were found in the interactions between gypsum content and acid type. The treatment order in sample S1 was S1T1, S1T2, and S1T3, with averages of 14.662, 12.513, and 12.023 mg kg⁻ ¹, respectively. For treatment order S2, the averages were 10.702, 9.592, and 9.925 mg kg⁻ ¹ for treatments S2T1, S2T2, and S2T3, respectively. The same table illustrates the interaction between soil gypsum content and acid application levels. Treatment S1L3 showed the highest average at 15.350 mg kg⁻ ¹, while the control treatment recorded the lowest average at 9.167 mg kg⁻ ¹. Conversely, treatment S2L3 recorded the highest average at 11.821 mg kg⁻ ¹, while the control treatment recorded the lowest average at 7.590 mg kg⁻ ¹. The table also shows significant differences between the type of acid and its application level, with treatment T1L3 achieving an average of 15.415 mg kg⁻ ¹, while the control treatment achieved an average of 8.378mg kg⁻ ¹. The results of the three-way interaction between soil gypsum content, acid type, and application level were presented. In sample S1, the S1T1L3 An average concentration of 18.073 mg kg1 was achieved with this treatment while the control treatment recorded the lowest concentration of 9.167 mg kg⁻ ¹. In sample S2, the S2T1L3 treatment achieved the highest mean concentration of 12.757 mg kg⁻ ¹, while the control treatment recorded the lowest concentration of 7.590 mg kg⁻ ¹.

Table 6. Available phosphorus (mg kg⁻ ¹) as affected by cow manure extract type and application level at 100 mg P kg⁻ ¹.

Mean	L3	L2	L1	Control	Extract	Soil
14.662	18.073	16.933	14.477	9.167	T1	S1
12.513	14.670	13.627	12.59	9.167	T2	S1
12.023	13.307	13.157	12.46	9.167	T3	S1
10.702	12.757	11.977	10.483	7.590	T1	S2
9.592	11.113	10.327	9.337	7.590	T2	S2
9.925	11.593	10.837	9.68	7.590	T3	S2
13.066	15.350	14.572	13.176	9.167	Mean	S1
10.073	11.821	11.047	9.833	7.590	Mean	S2
12.682	15.415	14.455	12.48	8.378	T1	Mean
11.053	12.892	11.977	10.963	8.378	T2	Mean
10.974	12.450	11.997	11.07	8.378	T3	Mean
—	13.586	12.809	11.504	8.378	L	Mean

LSD at 5%: S×T×L = 0.2625; T×L = 0.3712; S×L = 0.2143; S×T = 0.1856; L = 0.1515; T = 0.1312; S = 0.1072

S1 = 98 and S2 = 445 g kg⁻ ¹ gypsum; T1 = total humic substances, T2 = humic acid, T3 = fulvic acid; control = 0, L1 = 20, L2 = 40, L3 = 60 L ha⁻ ¹. LSD = least significant difference; NS = not significant.

Table 7 shows a significant reduction in available phosphorus with increasing soil gypsum content, with treatment S1 reflecting the highest average of 12.004 mg kg⁻ ¹, while treatment S2 recorded the lowest average of 9.753 mg kg⁻ ¹.

Based on the table above, there are significant differences in the types of acids used. The treatments were arranged in the following sequence: T1 – T3 – T2, with averages of 11.554, 10.617, and 10.464 mg kg⁻ ¹, respectively. As shown in the same table, there is a direct relationship between the amount of available phosphorus and the levels of acid utilization, with the average for treatment L3 being 12.248 mg kg⁻ ¹, while the average for the comparison treatment was 8.378 mg kg⁻ ¹. The table results showed statistically significant differences in the interactions between soil gypsum content and acid type. In sample S1, the treatment order was S1T1, then S1T2, then S1T3, with average doses of 12.636, 11.878, and 11.497 mg kg⁻ ¹, respectively. In treatment S2, the order was S2T1, then S2T3, then S2T2, with average doses of 10.473, 9.737, and 9.049 mg kg⁻ ¹, respectively. The same table illustrates the interaction between soil gypsum content and acid application levels, showing a marked advantage for treatment S1L3, which achieved the highest average at 13.444 mg kg⁻ ¹, while the control treatment achieved the lowest average at 9.167 mg kg⁻ ¹. In contrast, treatment S2L3 achieved the highest average at 11.051 mg kg⁻ ¹, whereas the control treatment achieved the lowest average at 7.590 mg kg⁻ ¹. Furthermore, the table indicates that there is no statistically significant interaction between soil gypsum content, acid type, and application levels when using 100 mg P kg⁻ ¹ triple superphosphate fertilizer.

Table 7. Available phosphorus (mg kg⁻ ¹) as affected by palm fronds extract type and application level at 100 mg P kg⁻ ¹.

Mean	L3	L2	L1	Control	Extract	Soil
12.636	14.377	14.073	12.927	9.167	T1	S1
11.878	13.237	13.003	12.107	9.167	T2	S1
11.497	12.720	12.43	11.673	9.167	T3	S1
10.473	12.223	12.013	10.063	7.590	T1	S2
9.049	9.843	9.963	8.8	7.590	T2	S2
9.737	11.087	10.887	9.383	7.590	T3	S2
12.004	13.444	13.169	12.236	9.167	Mean	S1
9.753	11.051	10.954	9.416	7.590	Mean	S2
11.554	13.300	13.043	11.495	8.378	T1	Mean
10.464	11.540	11.483	10.453	8.378	T2	Mean
10.617	11.903	11.658	10.528	8.378	T3	Mean
—	12.248	12.062	10.826	8.378	L	Mean

LSD at 5%: S×T×L = NS; T×L = 0.3807; S×L = 0.3108; S×T = 0.2692; L = 0.2198; T = 0.1904; S = 0.1554

S1 = 98 and S2 = 445 g kg⁻ ¹ gypsum; T1 = total humic substances, T2 = humic acid, T3 = fulvic acid; control = 0, L1 = 20, L2 = 40, L3 = 60 L ha⁻ ¹. LSD = least significant difference; NS = not significant.

Discussion

The cow-manure treatments consistently produced higher available phosphorus in S1 than in S2 (Tables 2, 4, and 6). This pattern is consistent with the calcium-rich conditions of gypsiferous soils, in which phosphorus availability can be constrained by precipitation and retention processes, as described in general soil chemistry [4, 12, 17]. Humic substances can influence phosphorus availability through calcium complexation, competition for reactive mineral surfaces, and interactions between organic matter and phosphate [3, 16, 26, 37]. These mechanisms provide plausible explanations for the observed responses; however, the present experiment measured available phosphorus and did not directly measure calcium complexation, adsorption energy, or microbial activity. Total humic substances generally produced the highest means. In cow-manure treatments, the overall humic-acid mean was slightly higher than the fulvic-acid mean, but their differences at 0, 50, and 100 mg P kg⁻ ¹ were smaller than the corresponding LSD values. Therefore, these small differences should not be interpreted as significant separation between the two fractions. Molecular characteristics and physiological effects of humic substances have been described previously [6, 7, 33, 34]. Increasing extract rate generally increased available phosphorus, consistent with studies of organic amendments and humus acids [2, 14, 15]. The significant three-way interactions at 50 and 100 mg P kg⁻ ¹ indicate that treatment responses depended on the combination of soil, extract type, and extract rate. The nonsignificant interaction without mineral phosphorus addition does not establish the absence of individual factor effects.

For palm-frond extracts, available phosphorus was also consistently higher in S1 than in S2 (Tables 3, 5, and 7). Total humic substances had the highest overall means at each mineral phosphorus level. Fulvic acid exceeded humic acid in the overall palm-frond means, although the difference at 100 mg P kg⁻ ¹ was smaller than the reported LSD for extract type. Within S1, humic acid often produced higher values than fulvic acid; within S2, the opposite pattern occurred. The initial soil pH values were 7.32 and 7.65, respectively, but these observational differences cannot isolate a

causal pH effect because the soils differed in several properties. Calcium complexation and interactions between humic fractions and phosphorus offer possible explanations [3, 26, 36, 37], rather than mechanisms demonstrated directly by this experiment. The three-way interaction was significant at 50 mg P kg^{-1} and nonsignificant at 0 and 100 mg P kg^{-1}. Nevertheless, mean available phosphorus increased with mineral phosphorus addition. The nonsignificant interaction at 100 mg P kg^{-1} therefore does not show that palm-frond extracts were ineffective. Previous Iraqi studies have reported benefits from combining organic materials with phosphorus fertilizers [15, 22, 23], while fertilizer formulation and placement can affect plant phosphorus nutrition [13]. Humic acid and foliar amendments have also improved nutrient availability in a field study [31]. These findings support further testing of the present extract treatments under crop-growing conditions. The two soils were not identical apart from gypsum content, so their response differences cannot be attributed exclusively to gypsum. Likewise, the incubation results do not establish an agronomic optimum, crop yield response, or the benefits of phosphorus rates exceeding 100 mg P kg^{-1}.

Conclusion

Available phosphorus was higher in the soil containing 98 g kg^{-1} gypsum than in the soil containing 445 g kg^{-1} gypsum. Increasing the application rate of cow-manure and palm-frond extracts generally increased available phosphorus, and total humic substances generally produced the highest overall means. The highest measured concentration was 18.073 mg kg^{-1} in S1 receiving cow-manure total humic substances at 60 L ha^{-1} with 100 mg P kg^{-1}. The results support further investigation of combined organic extracts and mineral phosphorus for gypsiferous soils. Field experiments and direct measurements of relevant chemical mechanisms are needed before identifying an agronomic optimum or prescribing application rates.

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