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Soil inorganic phosphorus fractions and phosphorus availability in calcareous soils under medium- and long-term organic farming practices

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ABSTRACT

Soil phosphorus management is critical in conventionally managed farms and organic farms. Knowledge about inorganic P (Pi) fractions, availability, and dynamics under different cropping systems; greenhouse and open field, locations with different climatic conditions (Al-Tuneib and Jordan Valley), and soil sampling dates (three dates) for medium- (5 years in Jordan Valley) and long-term (13 years in Al-Tuneib) organic farming is inadequate. Thus, this study was conducted to investigate the effect of these factors on soil Pi to assess the status of soil P to better manage organic farming, control stock soil P, and protect environment and water resources. Soil Pi sequential fractionation was performed using calcareous soil adapted procedure. Results indicated that Olsen P; a traditional P availability index, was higher in Al-Tuneib (in greenhouse) where possible P leaching can occur due to irrigation. Conversely, the most labile fraction (Ca_2-P) was significantly higher in Jordan Valley (in greenhouse), particularly, at the beginning of the rotation cycle (D1). However, Ca_2-P was higher in Al-Tuneib (in open field) at D1, whereas at D3 it was higher in Jordan Valley. Concerning the effect of cropping system, open field soils had generally higher Ca_2-P, except at D1 in Jordan Valley. Regarding Pi dynamics, Ca_2-P significantly increased over time, while the moderately labile fraction (Ca_8-P) decreased, revealing an inverse correlation. Results indicated that Ca_8-P was dynamically replenishing Ca_2-P, providing insight into soil P dynamics in organic farming. Our findings will help managing soil P inputs, stock soil P and P leaching risk under organic farming.

Keywords: available P, P fractionation, sustainable P management, soil P accumulation, land use, organic amendments, environmental risk assessment.

INTRODUCTION

Phosphorus (P) is an essential macronutrient that is required by plants in relatively large amounts (approximately 0.2 to 0.8%) (Mengel and Kirkby, 1987). As a matter of fact, plants just use 10 to 20% of the entire added P to the soil as inorganic P (Helfenstein et al., 2018). In current agricultural practices, farmers add chemical P fertilizers to increment crop development and production. However, intensified use of chemical phosphorus fertilizers result in extreme buildup of P in soils (Jiang et al., 2021). Modifying the input of P fertilizers, diminishing losses of P, and reusing P in organic-wastes are effective approaches to decrease chemical P inputs globally (Mortola et al., 2019; McConville et al., 2020; Qaswar et al., 2020).

In organic agriculture, animal wastes are an important source for delivering elements including P and reloading soils with organic matter. Phosphorus effective utilization in agriculture necessitates precise recommendations of P fertilizer. Thus, precise assessment of the plant-available P not only in different soils but also in soils under different climatic conditions as well as different cropping systems is required to avoid or at least control P buildup in surface soil layers and possible occurrence of eutrophication and pollution of surface and ground water resources.

In soils, P depletion in the liquid phase can be replenished by means of the desorption of adsorbed P, weathering and dissolution of sparingly soluble P rocks and minerals such as Ca-, Fe- and Al-phosphates, or the mineralization of organic P (Brady and Weill, 2002). However, the slow release of P from these reservoirs resulted in the application of additional P sources including chemical fertilizers, animal wastes, plant residues, etc. to maintain crop production and counterbalance P removed in the biomass after harvesting. In organic agriculture, the use of soluble chemical P fertilizers is not allowed by EU guidelines (European Union 2007, 2008), which conforms to the concept of organic agriculture that rely on soils that are biologically active to supply growing crops with nutrients (Lampkin and Measures, 2001). Such ban is also based on the worries about the environmentally adverse effect of the production of chemical P fertilizers and the compromised food supplies sustainability that depend upon a nonrenewable P source (Soil Association, 2010). In addition, even the P-containing recycled organic wastes embraces several regulatory restrictions on production processes and composition (Løes et al., 2017). Nevertheless, Cooper et al. (2018) reported that farm scale data came from some European countries did not show deficits in extractable P; the results of 93% of the sampled sites fell into class 3 (sufficient) or above. Field data from Germany also demonstrated sufficient or higher concentrations of P phytoavailability for arable and grassland on 60% of sampled sites. Similarly, a recent analysis of soil samples (data not shown) taken from the organic farms; where the current study was carried out, revealed that plant available P and soil P stock exceeded the target values and were rated as "rather high"; although soil properties, characteristics, and application rates of the used organic amendments, and climatic conditions are different than those of Cooper et al. (2018). Therefore, soil rational management needs information on P fractions present in the soil (Cordell et al., 2009) and their transformation, as this data is critical for detecting the phytoavailability as well as mobility of P in soils and the eutrophication risk (Esteller et al., 2009). Accordingly, adjusting the utilization of various sources of P, including animal wastes, is vital to enhance the effectiveness of P management in organic agriculture (Lun et al., 2018; Pavinato et al., 2020). A probable solution to this situation is adding biowastes based on plant P requirements rather than plant nitrogen demands.

Worth mentioning that traditional soil analysis procedures possibly underrate P phytoavailability from soils amended with organic materials (Steffens et al., 2010). Despite the constraints related with the use of traditional extractants of P to express the phytoavailability of soil P in organically managed soils, most publications, including organic agriculture research, applied these standard techniques. However, insufficient data about the fractions of P and their dynamics in the soil environment of organic agriculture is available. Therefore, since inorganic P is the preferred form for plant uptake, knowledge of the nature and transformation of P fractions in the soil environment under organic agriculture is a main priority for abundantly understanding phytoavailability of P, potential for P losses, and sustainability of related organic agricultural practices. To investigate the inorganic P (Pi) forms and transformation in the soil, the sequential fractionation scheme for calcareous soils based on methods described by Jiang and Gu (1989) was implemented. The current study was conducted in an organic farm located in two different sites in terms of Köppen Climate Classification, Al-Tuneib (in Amman) and Abu Obaida (in the Jordan Valley) where organic farming is practiced since 2010 and 2018, respectively. Different aspects that might differentiate the current study from previously published researches were investigated and discussed. Such aspects were the main reason of choosing these two different locations to conduct the current research. These aspects reflected the variability in climatic and soil conditions, temporal differences within and between these locations, and different farming systems with variable practices. Thus, the current research aimed at evaluating the medium- and long-term influence of the organic agriculture practices on the different P fractions in the soil environment, evaluating the short-term dynamics of P in the soil of two sites under different conditions, and assessing the effect of management practices on P fractions and dynamics.

MATERIALS AND METHODS

Study area

The current study was conducted in an organic farm located in two different sites; Al-Tuneib (45 ha) and Abu Obaida (5 ha) located in Amman and the Jordan Valley, respectively. Organic farming is practiced in these two locations, respectively, for 13 and 5 years. This will provide us with the possibility of studying the medium- and long-term impact of organic agriculture on the different fractions of soil P under different conditions (Table 1).

The studied soils are usually cultivated with more than 70 varieties of crops throughout the year on a seasonal basis, including tomatoes, cucumbers, peppers, eggplant, corn, watermelon, cantaloupe, and others in greenhouses and in the open field. In these two sites, the organic fertilizers applied and mixed with the surface soil are; fermented and sometimes unfermented sheep manure, poultry manure produced on site as a by-product of a project for organic eggs, and compost. Soil is plowed and then chopped after the application of manure. The rate of application of these different organic fertilizers depends on the variety and the planting date. These application rates were documented at time of soil sampling as shown in Table 2.

Data collection

Soil sampling

Forty-eight topsoil samples (0–30 cm) were randomly collected from the above-mentioned sites using a soil auger. Soil samples were collected from the top 30 cm, as this soil layer is where organic amendments are incorporated and where most soil biota as well as plant roots mainly concentrated. To ensure spatial independence and representativeness, random soil samples were taken at sufficient distances from each other. In each site, soil samples were collected from greenhouses (GH) and from the open field (OF). Soil sampling was carried out three times during the growing season of a single rotation cycle: the first sampling was carried out after land preparation and manure application or at early crop development stage (at the beginning of April), the second sampling was carried out at mid-season stage (end of May), and the third sampling was carried out at time of harvesting (beginning of July). The fresh soil samples were immediately transported to the lab. Samples were air-dried and crushed to pass through 2-mm sieve, or less when necessary, prior to chemical analysis. Samples were stored at 4 °C.

Soil analysis

Soil pH in a 1:1 soil:water suspensions (Thomas, 1996), electrical conductivity (EC) in a 1:1 soil:water suspensions (US Salinity Laboratory Staff, 1954), organic matter content (Nelson and Sommers, 1996), particle size distribution determined using the hydrometer method (Gee and Bauder, 1986), and calcium carbonate equivalent (Loeppert and Suarez, 1996) were determined according to the standard methods (Table 3). Olsen-P fraction was also extracted by sodium bicarbonate (Olsen and Sommers, 1982) and considered as P availability index (Tables 4 and 5).

Inorganic phosphorus sequential fractionation scheme

The inorganic phosphorus sequential fractionation scheme was implemented according to Jiang and Gu (1989) for calcareous soils, which was later applied and/or slightly modified by Adhami et al. (2006), and He et al. (2015): One gram of air-dried sieved soils (2 mm or less when necessary) was extracted in 100-mL PP (polypropylene) centrifuge tubes. A brief methodology is given below; each of the chemical fractions will be extracted as follows:

Table 1. Conditions prevailing in the study area

Parameter	Al-Tuneib	Abu Obaida
Elevation (m)	768 a.s.l	209 b.s.l
Annual precipitation (mm)	150-300 mm	<200 mm
Annual potential ET (mm)	1974	2200
Mean annual temperature (°C)	18.8	24.6
Köppen climate classification	BSh	BWh

1. Ca2-P (dicalcium phosphate/labile P) was extracted with 0.25 M $NaHCO_3$ (pH 7.5).
2. Ca8-P (octacalcium phosphate/moderately labile P) was extracted with 0.5 M NH_4Ac (pH 4.2).
3. Al-P (P adsorbed by Al oxides/Moderately labile P) was extracted with 0.5 M NH_4F (pH 8.2).
4. Fe-P (P adsorbed by Fe oxides/moderately labile P) was extracted with 0.1 M $NaOH\text{-}Na_2CO_3$.
5. O-P (occluded phosphate; P incorporated or trapped in Fe oxide coatings/stable P) was extracted with 0.3 M $Na_3C_6H_5O_7\text{-}Na_2S_2O_4\text{-}NaOH$.
6. Ca10-P (P present as apatite/stable P) was extracted with 0.5 M H_2SO_4.

Inorganic phosphorus (Pi) in the soil extracts was determined by molybdate-ascorbic acid method (Murphy and Riley, 1962) using a colorimetric absorption spectrophotometer at 880 nm.

Statistical analysis

The statistical analyses followed standard procedures for parametric tests (i.e., t-test and ANOVA) using SAS software (SAS Institute, 2012). The Student's t-test was used to evaluate the differences between two treatments, while one-way analysis of variance (ANOVA) was employed when more than two treatments were compared. After significant differences were identified, means were separated by the Least Significant Difference (LSD) test at the 95% confidence level ($p < 0.05$).

RESULTS AND DISCUSSION

Inorganic phosphorus sequential fractionation scheme

The method of Jiang and Gu (1989) and its modifications (Adhami et al., 2006; He et al., 2015) were designed to analyze for different inorganic P fractions in calcareous soils that are related with plant available P and its mobility in these soils. Thus, this method was adopted to investigate the different fractions of inorganic P in the soils of the current study. The first Pi fraction (dicalcium phosphate) extracted with $NaHCO_3$ represents as easily soluble fraction that is labile, plant available, and can replenish the depleted soil solution Pi. Such fraction is considered moderately mobile compared with other fractions. The importance of this Pi fraction is that it is considered as a short-term reserve. The second Pi fraction (octacalcium phosphate) extracted with NH_4Ac, which is a moderately crystalline P mineral, is moderately

Table 2. Type and amounts of added organic fertilizers

Location	Type of organic fertilizer	Time of application 1	Application rate of organic fertilizer (kg m^{-2})	Time of application 2	Total amount added
Greenhouse at both Al-Tuneib and Abu Obaida	Composted manure	Before the growing cycle	0.81	An extract of a mixture of 30 kg manure and 200 L of water is added along with irrigation water at the middle of season	Approx. 350 kg of composted manure per greenhouse (GH area = 432 m^2)
Open field at both Al-Tuneib and Abu Obaida	Composted manure	Before the growing cycle	0.60	An extract of a mixture of 30 kg manure and 200 L of water is added along with irrigation water at the middle of season	300 kg of composted manure (per 500 m^2)

Table 3. Some physicochemical properties of the studied soils

Soil properties	Al-Tuneib		Abu Obaida	
	GH	OF	GH	OF
$pH_{1:1}$	7.77	7.85	7.58	7.79
$EC_{1:1}$ (dS m^{-1})	1.41	1.25	1.03	0.88
OM (%)	1.82	2.62	1.38	1.45
$CaCO_3$ (%)	14.7	12.7	16.2	18.0
Soil texture	Loamy to clay loam		Sandy loam to silty clay	

(slowly) available to plants during the growing season and its mobility is also low to moderate. This Pi fraction is considered as a transition fraction between labile pool and nonlabile or stable Pi pools. The specific importance of this Pi fraction is prominent in poorly fertilized soils. The third as well as the fourth Pi fractions; i.e. phosphorus adsorbed to or precipitated with aluminum and iron (hydro)oxides, represent low to moderate plant available Pi. Although their availability is problematic, such fractions can be solubilized in the presence of root exudates (e.g. organic acids), through the release of protons from roots, and/or enhanced microbial activity and respiration in the vicinity of roots. Therefore, these two Pi fractions can ultimately be considered as a slow-release source of Pi. The fifth Pi fraction (the occluded phosphate) represents a nonlabile (stable) fraction that has no importance in the short-term Pi availability to plants. Such fraction is not liberated or solubilized by the different mechanisms that might mobilize the third and fourth Pi fractions; i.e. Al-P and Fe-P. The last (sixth) fraction (P present as apatite) represents a highly crystalline P mineral. Its availability and mobility are neglected under normal soil conditions (Wang et al., 2022; Wang et al., 2023; Biassoni et al, 2023; He et al., 2023; Candia-Díaz et al., 2025).

Olsen P as the traditional P availability index

In the current study, Olsen P was only determined at the beginning of April; i.e. at the beginning of the investigated rotation cycle in both locations under greenhouse and open field conditions. The reason was because the critical level of Olsen P under the conditions of the current study that is expected to achieve high soil fertility, crop yield (of different crops grown in this farm in the two locations under possible different soil and climatic conditions), and phosphorus use efficiency is neither documented nor experimentally determined. Ibrahim et al. (2021) mentioned that such critical or optimal level of Olsen P is indeed affected by these factors. In the latter study, the optimal level of Olsen P for *Zea mays* L. grown in black soil was found to be 28 mg kg^{-1}. In earlier investigation, Recena et al. (2015) clearly reported that Olsen P was not an accurate tool to predict uptake of P by plants in their studies 17 soils that are typical soil types of the Mediterranean part of Spain. In addition, Ara et al. (2018) found that Olsen P as well as other forms of extractable P, followed the application of different organic P materials to alkaline soils, increased with time only up to 30 days after application. However, the magnitude of increase varied with the type of added organic P material. Olsen P was also found to be only correlated with added material. For all these reasons, Olsen P was only determined once in the current study. Our results showed that both location and cropping system had significant effect on Olsen P. An exception is the effect of cropping system on Olsen P in the Jordan Valley (Abu Obaida) (Tables 4 and 5). Olsen P values were higher in soils of Al-Tuneib in both GH and OF than those in the Jordan Valley (Tables 4 and 5). Only in Al-Tuneib, Olsen P was significantly higher in the GH than in the OF (Tables 4 and 5).

According to Siebers at al. (2017), climate regimes may affect the P cycle in soil, which results in changes in the P fractions. In the latter

Table 4. Effect of location on Olsen P (mg kg^{-1}) (at the beginning of April)

Location	GH	OF
Jordan Valley (Abu Obaida)	35.8 b ± 0.28	38.5 b ± 3.32
Al-Tuneib	94.0 a ± 2.83	59.0 a ± 1.77

Note: Values are mean ± standard deviation. In columns, means with different letters are significantly different ($p < 0.05$) according to t-test (n = 2).

Table 5. Effect of cropping system on Olsen P (mg kg^{-1}) (at the beginning of April)

Cropping system	Jordan Valley (Abu Obaida)	Al-Tuneib
GH	35.8 a ± 0.28	94.0 a ± 2.83
OF	38.5 a ± 3.32	59.0 b ± 1.77

Note: Values are mean ± standard deviation. In columns, means with different letters are significantly different ($p < 0.05$) according to t-test (n = 2).

study, it was evidently reported that climatic gradients; e.g. increasing temperature, resulted in transforming phosphorus forms towards the more nonlabile or stable pools of phosphorus. Similar results were reported by Hou et al. (2018). On the other hand, the higher Olsen P under greenhouse conditions in comparison with open field in Al-Tuneib can be possibly attributed to that P losses through leaching and/or runoff is minimal in greenhouses because they are physically covered, which might lead to a higher Olen P values (Table 5). Moreover, greenhouses in the current study received relatively higher total amounts of organic materials as shown in Table 2, which can contribute to higher Olsen P. Unfortunately, comparisons between greenhouses and adjacent open fields in organic farms under similar cultural practices concerning Olsen P are not available in the literature. Ultimately, from the environmental point of view, the high value of Olsen P observed in Al-Tuneib under greenhouse conditions (Table 5) might impose, however, a problem related to possible P leaching in such calcareous soil under irrigation. A warning that was also raised by Ortiz et al. (2023) under somehow similar conditions.

Inorganic phosphorus fractions

It is noteworthy that literature dealing with and discussing the combined effect of location, climate, time, and cropping system is scant. For this reason, current results were presented and discussed as follows. Further investigations concerning the combined effect of these factors and other factors deserve attention.

Effect of location on Pi fractions

Results presented in Table 6 indicate that, under greenhouse conditions, the most labile or plant available Pi fraction (i.e. Ca_2-P) was significantly higher in the Jordan Valley (Abu Obaida) than that in Al-Tuneib at the beginning of the rotation cycle (D1). However, at the end of May (D2) as well as at the end of the rotation cycle (D3), location has no significant effect on this Pi fraction. In general, other Pi fractions were significantly higher in Al-Tuneib regardless of sampling date except for Fe-P at D3 (Table 6). Concerning the effect of location under open field conditions, the contrary was observed at D1 and at D3; i.e. the most labile Pi fraction was higher in Al-Tuneib at D1 while it was higher in the Jordan Valley at D3. Generally, other Pi fractions were also significantly higher in Al-Tuneib regardless of sampling date except for Ca_8-P at D1 and Al-P and Fe-P at D3 (Table 6).

Results indicated that Pi fractions (from Ca_8-P to the most stable one Ca_{10}-P) were mostly significantly higher in Al-Tuneib under both greenhouse and open field conditions, which can be attributed to the fact that organic farming is practiced in this location for longer period of time (13 years versus 5 years in the Jordan Valley/Abu Obaida). Moreover, this can also be related to recent application of organic materials before and in the course of the investigated rotation cycle, which is in agreement with Liu et al. (2022). Similar results were reported by Zhang et al. (2022). In the latter study, where organic materials and chemical fertilizers were added to three non-acidic soils (pH 7.6 to 8.6) for a period of more than 10 years, Ca_8-P, Al-P, Fe-P, and even Ca_{10}-P were all increased compared with soils amended for a shorter period. However, as it was mentioned earlier, the observed increase should be carefully considered because it might increase the risk of pollution from organic farming diffusing into water resources (Song et al., 2017).

Interestingly, it seems that no clear relationship exists between the most labile Pi fraction (Ca_2-P) and Olsen P at D1 (Tables 4 and 6). Both Ca2-P and Olsen P extracted at the beginning of the rotation cycle seem only to correlate under open field conditions while, under greenhouse conditions, no relationship is observed. These results are in agreement with Hu et al. (2012). In the latter study, it was reported that such relationship might vary with, among others, crops or management conditions.

The current results of Pi fractions (Table 6) are much higher than those reported by Song et al. (2017) except for the most labile fraction (Ca_2-P), Ca_8-P and O-P for a 4-year greenhouse experiment where soil was amended with different fertilization modes including organic manure. Song et al. (2017) found that the concentration of Pi in the surface soil layer (0–20 cm) after 4 years of organic manure application was 140.99, 293.36, and 475.01 mg P kg^{-1}, respectively for Ca_2-P, Ca_8-P and O-P. Moreover, the current results of particularly Ca_8-P are within the range (72-314 mg P kg^{-1}) reported by Mostashari et al. (2008) in calcareous soils.

In addition, our Ca_{10}-P results were also comparable to those found by Mostashari et al. (2008) (up to 700 mg kg^{-1}). Total P reported in the latter study ranged from 700 to 7778 mg kg^{-1}. In addition, Al-P and Fe-P were mostly significantly higher in Al-Tuneib than that in the Jordan Valley (Abu Obaida) regardless of the cropping system except for Al-P at D3 in the open field and Fe-P at D3 in both cropping systems (Table 6). Our results are in agreement with Liu et al. (2022) and Zhang et al. (2022). The content of Al-P and Fe-P was much higher than other Pi fractions except Ca_{10}-P (Table 6). These amounts are within the range reported by Zhao et al. (2023). In the latter study, Zhao et al. (2023) found that Fe-P and Al-P dominated the P speciation (using modified Hedley P fractionation) in acidic soils while Fe-P, Al-P, and Ca-P increased in alkaline soils (pH 7.74–8.04). Zhao et al. (2023) reported the amount of P associated with free, amorphous, and crystalline Fe and Al oxides, ranged from 240.9 to 1266.3, from 127.3 to 1048.4, and from 36.9 to 454.3 mg kg^{-1}, respectively.

Effect of cropping system on Pi fractions

In general, results showed that the content of Pi was significantly higher under greenhouse conditions in both locations and regardless of sampling dates (Table 7). Nevertheless, few exceptions were found; i.e. Ca_2-P at D3 in Abu Obaida and at D1 in Al-Tuneib as well as Ca_8-P at D1 in Abu Obaida and at D1 and D3 in Al-Tuneib under open field conditions (Table 7). Noteworthy, such exceptions are confined to only Ca_2- and Ca_8-P under open field conditions. Although scant literature directly compared between the effect of open field and greenhouse conditions in organic farming on Pi fractions in alkaline or calcareous soils, a possible reason is that soil organic matter (OM%) was higher in the open field in both locations (Table 3). Song et al. (2017) found that high Ca_2-P and Ca_8-P could be due to higher soil organic matter in the topsoil. In the latter study, it was indicated that organic matter could occupy sorption sites, which resulted in less retention of phosphorus. Moreover, the observed high Al-P and Fe-P (Table 7) particularly under greenhouse conditions in both locations regardless of sampling dates might indicate that the previous and current fertilization regime applied in the investigated organic farm has adversely affected the dynamic balance between labile and moderately labile Pi fractions especially under greenhouse conditions. The current results are in agreement with Song et al. (2017).

Table 6. Effect of location on the content of different P fractions under greenhouse and open field conditions

Location	Date	Greenhouse					
		Ca_2-P	Ca_8-P	Al-P	Fe-P	O-P	Ca_{10}-P
		mg kg^{-1}					
JV	D1	139.8 a ± 0.79	183.3 a ± 9.16	482.8 b ± 2.87	533.8 b ± 2.22	293.4 b ± 5.56	717.7 b ± 4.32
Al-Tuneib		132.8 b ± 3.70	192.8 a ± 5.04	604.2 a ± 15.38	657.2 a ± 6.08	460.6 a ± 2.64	864.4 a ± 107.6
JV	D2	139.6 a ± 3.50	121.9 b ± 3.44	590.0 b ± 2.08	615.8 b ± 4.89	392.4 b ± 2.97	947.7 b ± 6.60
Al-Tuneib		145.9 a ± 4.29	138.3 a ± 9.98	727.9 a ± 6.61	640.8 a ± 6.22	612.3 a ± 3.79	988.4 a ± 13.98
JV	D3	169.7 a ± 13.48	71.9 b ± 3.44	675.8 b ± 0.95	589.8 a ± 0.85	622.9 b ± 0.71	963.2 b ± 6.60
Al-Tuneib		156.8 a ± 6.59	88.3 a ± 9.97	763.8 a ± 1.03	528.1 b ± 0.78	838.7 a ± 0.76	993.9 a ± 1.86
Location	Date	Open field					
JV	D1	135.1 b ± 1.09	215.3 a ± 8.83	401.8 b ± 8.62	452.9 b ± 11.35	288.8 b ± 2.39	718.5 b ± 5.06
Al-Tuneib		143.3 a ± 2.48	203.2 b ± 4.20	580.5 a ± 2.94	631.7 a ± 5.74	385.7 a ± 17.02	762.7 a ± 2.58
JV	D2	140.6 a ± 3.45	125.0 b ± 1.55	583.5 b ± 2.58	603.6 b ± 3.30	381.3 b ± 5.17	935.2 b ± 1.71
Al-Tuneib		144.7 a ± 4.01	145.6 a ± 5.57	717.9 a ± 1.29	629.6 a ± 2.06	601.7 a ± 2.69	971.2 a ± 17.06
JV	D3	204.9 a ± 22.87	75.0 b ± 1.55	675.9 a ± 1.29	586.5 a ± 0.81	619.4 b ± 0.22	950.7 b ± 1.71
Al-Tuneib		157.4 b ± 5.63	95.6 a ± 5.55	637.0 b ± 0.94	426.0 b ± 0.52	653.1 a ± 0.91	982.1 a ± 11.31

Note: Values are mean ± standard deviation. In columns for each date and cropping system, means with different letters are significantly different ($p < 0.05$) according to t-test ($n = 4$). D1: soil samples collected at the beginning of April, D2: end of May, and D3: beginning of July.

The cropping system did not affect the most stable Pi fraction (i.e. Ca_{10}-P) in both locations regardless of sampling dates except for Abu Obaida at D3 (Table 7). This indicates that Ca_{10}-P is less sensitive Pi fraction to different cropping systems. Similarly, Khan et al. (2022) reported that the recalcitrant fraction of Pi (mainly Ca_{10}-P) does not vary much with different management practices on short and medium term.

Effect of sampling date on Pi fractions

Figure 1 demonstrated the dynamics of soil P for each Pi fraction, cropping system, and location. Soil P dynamics of different Pi fractions were generally the same regardless of cropping system and location. Similar results were reported in the literature. Bian et al. (2022) found that although the long-term cropping of cucumber under greenhouse conditions (soil pH 7.5) resulted in increasing both available P as well as total P, the ratio of labile P to total P was not significantly affected. In the latter study, it was reported that such cropping system also increased soil actinomycetes, which contributed to the build-up of soil non-labile P. He et al. (2023) indicated that soil pH has the most prominent effect on the proportions of all soil P fractions followed by total P concentration, soil O.C., soil depth, and biome. Under the conditions of the current study, soil pH, total P concentration (data not shown), and soil depth were almost the same. Moreover, Zhao et al. (2023) reported that chemical speciation and soil P distribution were largely determined by soil pH and Fe/Al fractions across different locations.

Interestingly, the most available or labile Pi fraction (i.e. Ca_2-P) significantly increased with time particularly at the third sampling date (D3). In parallel, the moderately labile P (the second most available Pi fraction; i.e. Ca_8-P) significantly decreased with time. Pearson correlation analysis between these two fractions revealed highly significant correlation coefficients (two-tailed $p < 0.01$). Correlation coefficients of -0.79, -0.85, -0.77, and -0.73, respectively for open field in Al-Tuneib, GH in Al-Tuneib, open field in JV, and GH in JV. Such results demonstrated that Ca_2-P and Ca_8-P are inversely related and that the increase in Ca_2-P is accompanied by a decrease in Ca_8-P with time (Figure 1). On the other hand, the Ca_8-P fraction was found to be inversely correlated with other Pi fractions except for Fe-P. The overall correlation coefficients between Ca_8-P and Al-P, Fe-P, O-P, and Ca_{10}-P were -0.68, 0.07, -0.74, and -0.80, respectively. The current results might indicate a dynamic transformation of Pi under the organic

Table 7. Effect of cropping system on the content of different P fractions in the Jordan Valley and Al-Tuneib

Cropping system	Date	Jordan Valley (Abu Obaida)					
		Ca_2-P	Ca_8-P	Al-P	Fe-P	O-P	Ca_{10}-P
		mg kg^{-1}					
GH	D1	139.8 a ± 0.79	183.3 b ± 9.16	482.8 a ± 2.87	533.8 a ± 2.22	293.4 a ± 5.56	717.7 a ± 4.32
OF		135.1 b ± 1.09	215.3 a ± 8.83	401.8 b ± 8.62	452.9 b ± 11.35	288.8 a ± 2.39	718.5 a ± 5.06
GH	D2	139.6 a ± 3.50	121.9 a ± 3.44	590.0 a ± 2.08	615.8 a ± 4.89	392.4 a ± 2.97	947.7 a ± 6.60
OF		140.6 a ± 3.45	125.0 a ± 1.55	583.5 b ± 2.58	603.6 b ± 3.30	381.3 b ± 5.17	935.2 a ± 1.71
GH	D3	169.7 b ± 13.48	71.9 a ± 3.44	675.8 a ± 0.95	589.8 a ± 0.85	622.9 a ± 0.71	963.2 a ± 6.60
OF		204.9 a ± 22.87	75.0 a ± 1.55	675.9 a ± 1.29	586.5 b ± 0.81	619.4 b ± 0.22	950.7 b ± 1.71
Cropping system	Date	Al-Tuneib					
GH	D1	132.8 b ± 3.70	192.8 b ± 5.04	604.2 a ± 15.38	657.2 a ± 6.07	460.6 a ± 2.64	864.4 a ± 107.6
OF		143.3 a ± 2.48	203.2 a ± 4.20	580.5 b ± 2.94	631.7 b ± 5.74	385.7 b ± 17.02	762.7 a ± 2.58
GH	D2	145.9 a ± 4.29	138.3 a ± 9.98	727.9 a ± 6.61	640.8 a ± 6.22	612.3 a ± 3.79	988.4 a ± 13.98
OF		144.7 a ± 4.01	145.6 a ± 5.57	717.9 b ± 1.29	629.6 b ± 2.06	601.7 b ± 2.69	971.2 a ± 17.06
GH	D3	154.0 a ± 4.23	83.7 b ± 4.20	764.3 a ± 0.30	527.7 a ± 0.32	838.9 a ± 0.78	994.2 a± 2.14
OF		157.4 a ± 5.63	95.6 a ± 5.55	637.0 b ± 0.94	426.0 b ± 0.52	653.1 b ± 0.91	982.1 a ± 11.31

Note: Values are mean ± standard deviation. In columns for each date and location, means with different letters are significantly different ($p < 0.05$) according to t-test ($n = 4$). D1: soil samples collected at the beginning of April, D2: end of May, and D3: beginning of July.

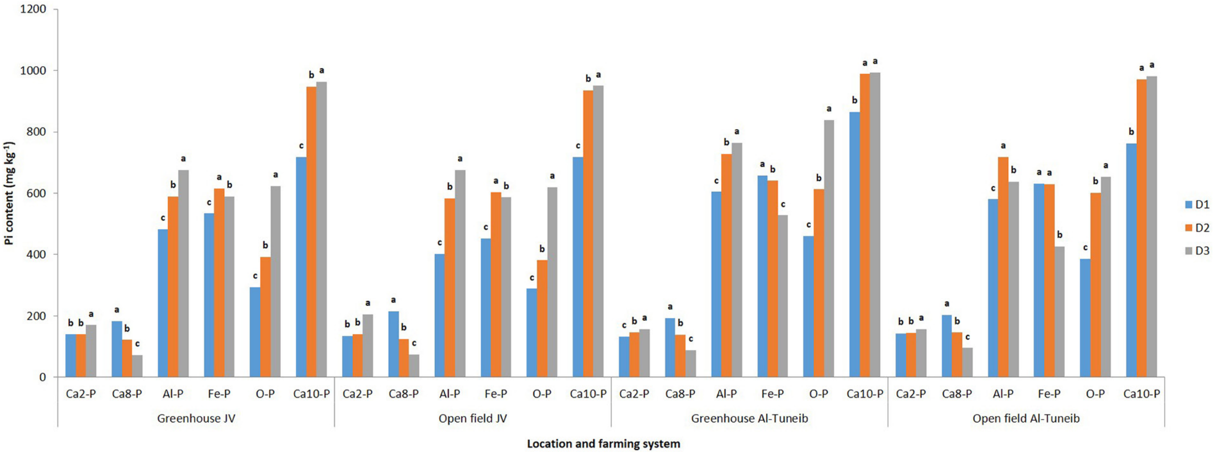

Figure 1. Effect of sampling date on the content of different Pi fractions. Values are means. For each Pi fraction and cropping system in each location, means with different letters are significantly different ($p < 0.05$) according to t-test (LSD; not shown) ($n = 4$). D1: soil samples collected at the beginning of April, D2: end of May, and D3: beginning of July

farming system practiced in the investigated farm regardless of cropping systems and locations. In general, our results present evidence that, under the conditions of the current study, the Ca_2-P and Ca_8-P fractions are dynamically connected. While generally all other Pi fractions that represent the moderately (less labile) to the most stable fractions were increasing with time, the Ca_8-P was dynamically replenishing the Ca_2-P fraction. This finding shed light on the possibility of considering these two fractions of soil Pi in order to further understand the dynamics of soil phosphorus. The inclusion of analyzing these two fractions in routine analysis for soil available P might contribute to comprehensive reviewing soil P inputs and management to remediate the risk of potential intensification in legacy soil P and the associated P leaching and eutrophication risks even under organic farming systems as found in the current study. Although under different conditions, similar relationship was reported by Zhao et al. (2019).

CONCLUSIONS

The accumulation of soil P is expected in organic farms due to the lack of soil-based P monitoring and management. In addition, no threshold for different soil P availability indices including the Olsen P are well established for different crops and/or management practices in organic farming systems. Although very common, the Olsen P might not be the proper tool to review soil P inputs. The relationship between the latter and the most labile soil Pi fractions; i.e., Ca_2-P and Ca_8-P, is not clear and needs further investigation. Our findings suggest that analysis for these two Pi fractions should be included in routine soil analysis for available P to better manage soil P in a sustainable way. This strategy would help maintaining available P at an appropriate level. Moreover, the observed negative correlation between Ca_2-P and Ca_8-P expands our knowledge about soil P dynamics under organic farming conditions through understanding the importance of the balance between these two fractions over time for reviewing soil P management and crop P requirements. Such balance was found to depend mainly on time rather than other factors, such as cropping system and location with possible climatic differences. The relatively high soil Pi content observed in different cropping systems and locations should be considered in current environmental risk assessment in the investigated soils.

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