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Review article

A review on phosphorus drip fertigation in the Mediterranean region: Fundamentals, current situation, challenges, and perspectives

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ABSTRACT

The Mediterranean agricultural sector faces many challenges related to water and mineral resource use for crop production and food security for an exponentially growing population. Phosphorus drip fertigation has recently emerged as an efficient and sustainable technique to improve water and nutrient use efficiency under such challenging pedoclimatic conditions. The classical methods for administering standard P fertilizers to crops (broadcasting and banding) have shown their limitations in terms of P acquisition and use efficiency. More than 60 % of applied P through dry P fertilizers is rapidly transformed into recalcitrant P forms and subsequently lost by soil erosion increasing the effects of P eutrophication issues on the ecosystem's sustainability. The emergence of new advanced irrigation technologies like high-frequent drip irrigation must be accompanied by the development of new P formulations with high water solubility and greater P use efficiency. This review illustrates the state of the art for P fertilizers used in Mediterranean agriculture in the last decades. An overall description is provided for the P fertilizer formulas, their physicochemical properties, as well as their suitability for drip fertigation systems and the consequent effects of their application on photosynthesis, plant growth, and crop productivity. The key factors influencing P fertilizer transformations and use efficiency under drip fertigation systems are extensively discussed in this review with a focus on the differences between orthophosphate and polyphosphate formulations.

1. Introduction

The agricultural sector in the Mediterranean basin faces many challenges related to the use of water and mineral resources for crop production and food security. Most countries in arid and semi-arid areas suffer from water scarcity and soil nutrient depletion which severely impact the productivity of different cropping systems currently challenged by climate change and the high pressure on natural resources [1–3]. Moreover, climatic unpredictability and the increasing frequency of severe events such as drought and floods, as well as changes in radiation and temperature can result in agricultural product losses. Under these challenging pedoclimatic conditions, the development of innovative techniques and practices aimed at improving natural resource use efficiency is becoming a major concern, particularly for water and non-renewable resources like phosphate rock [4,5].

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Phosphorus (P) is an essential element for all living organisms and no other nutrient can perform its functions. P is a vital element for plant growth and development, classified as a macronutrient, meaning that it is required by crops in relatively high quantities. P is known to play an important role in many plant processes, including energy transfer, photosynthesis, sugar and starch transformation, nutrient flow within plant tissues, and crop yield elaboration [6,7]. According to several studies, P is becoming a limiting factor for crop production in many cropping systems [8–10].

Even though the use of standard P fertilizers (granular P fertilizer) has substantially improved crop yield and quality, P recovery by plant is still quite low when compared to other nutrients [11,12]. Most studies evaluating the use efficiency of dry P fertilizer found that crops take up only 10–25 % of the applied P within the same growing season [13]. Recently, phosphorus drip fertigation has been proposed as an efficient agricultural practice to improve P use efficiency by crops, as it delivers nutrients when and where plants need them [14,15]. However, the effectiveness of P drip fertigation systems as well as the impact of P fertigation on crop physiology and productivity still fluctuate and depend on a variety of factors including soil properties, fertilizer characteristics, as well as P application strategies [16–18].

This review is among the first reports discussing the current situation of water and mineral fertilizer resources and their use in the Mediterranean context with a focus on phosphorus fertigation as an innovative and efficient technique for improving mineral and water resources at the field scale. We summarize the recent studies conducted on phosphorus transformations and dynamics in the soil-plant continuum under P fertigation regimes. The impact of the chemical properties of mineral fertilizers on P solubility and suitability for drip fertigation was discussed, as well as the consequent effects of P nutrition and agronomic practices on plant photosynthesis, physiology, and productivity.

2. Water and fertilizer use in the Mediterranean agriculture

With the impacts of global climate change on the agriculture sector, especially on water resource availability and reliability, irrigation will play a key role in crop production systems in the next few years for many countries around the Mediterranean basin. As shown in Table 1, North Africa, and Middle East countries tend to be the most water-stressed countries in the Mediterranean. Under these drought conditions, agricultural water withdrawal will also increase in southern European countries (Spain, Portugal, and Greece) and irrigation water requirements will highly increase to reach a peak value. Moreover, decreasing precipitation and its high seasonal variation as well as the frequent and longer drought episodes may affect the phenology, yields, and quality of many crops in the Mediterranean region.

Drought, water scarcity, and soil nutrient deficiencies are the main challenges facing Mediterranean agriculture, causing substantial reductions in crop yields and quality. Accordingly, the development of efficient techniques for sustainable management of water and land resources is becoming a concern for many agricultural actors. Based on the data shown in Fig. 1, many countries in the Mediterranean basin have promoted the development of more efficient irrigation techniques. Although drip irrigation systems have the highest investment cost compared to other irrigation methods, it was largely supported and extended in several agroecosystems in the Mediterranean basin. The high efficiency of drip fertigation systems in terms of water and nutrient use is the main driver encouraging many governments and the private sector to carry out large-scale projects promoting drip irrigation. For example, in Morocco, The Green Morocco Plan Agricultural strategy launched in 2008 has developed a specific program for converting the surface irrigated area

Table 1
The situation of water resources in Mediterranean agriculture (derived from FAO [19]).

	Renewable water resources (10^9 m^3/year)	Agricultural water withdrawal (%)	Irrigation water requirement ($10^{\hat{}9}$ m^3/year)	Area salinized by irrigation (1000 ha)	Water Stress (%)
Albania	30.2	39.5	0.32	12	7.9
Algeria	11.7	64.1	2.51	NA	127.6
Bosnia & Herzegovina	37.5	NA*	NA	NA	2.2
Croatia	105.5	1.3	NA	NA	1.4
Cyprus	0.8	63.1	0.09	NA	29.8
Egypt	57.5	79.2	45.11	900	119.5
France	211.0	10.6	2.35	NA	25.7
Greece	68.4	87.8	5.44	NA	19.4
Israel & Palestine	1.8	57.8	0.56	27.82	122.4
Italy	191.3	49.7	8.02	NA	30.1
Jordan	0.9	53.1	0.30	2.3	100.1
Lebanon	4.5	38.0	0.53	1	58.8
Libya	0.7	83.2	1.83	190	822.9
Morocco	29.0	87.8	5.82	150	49.7
Portugal	77.4	78.7	2.02	NA	18.4
Serbia	162.2	13.5	0.02	NA	5.3
Slovenia	31.9	0.4	0.001	NA	6.0
Spain	111.5	66.9	14.06	NA	43.7
Syria	16.8	87.5	7.12	60	125.9
Tunisia	4.6	77.4	1.55	86	121.1
Turkey	211.6	86.2	25.14	1519	43.8

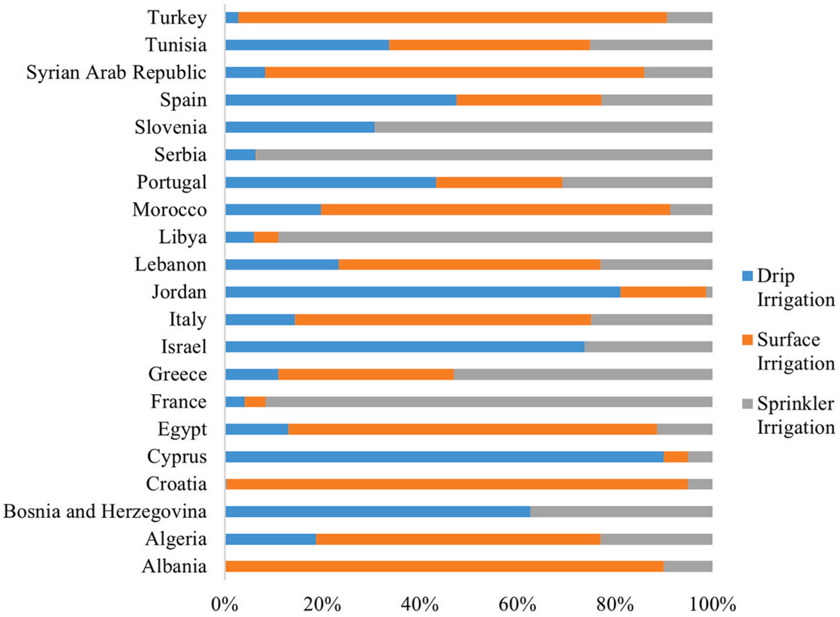

Fig. 1. Irrigation systems in the Mediterranean countries [19].

to drip irrigation systems, so far, the program has covered 0.6 million hectares, which represents 20 % of the irrigated area in Morocco [20]. Similar trends were reported in most Mediterranean countries, data shown in Fig. 1. In addition to water availability, several authors have assessed the impact of climate change on soil resources in the Mediterranean basin. They reported that the recurrent and longer dry conditions will highly alter some physicochemical proprieties of soil, especially soil structure and organic matter content [21,22]. In some cases, such as in North Africa and Turkey, the soil will be highly vulnerable to salinity and erosion problems, resulting in a decrease in soil fertility and a stagnation and/or reduction of crop yield. The average yield of the main crops grown in the Mediterranean region not increased significantly over the last three decades compared to European or American regions. Most crops in the Mediterranean displayed little increase (or stagnation) in yields, especially for pulses, fruits, oil crops, and cereals [23–25]. Given the expected impact of climate change on soil fertility and crop productivity, the adoption of innovative and efficient agricultural practices becomes more and more essential for ensuring food security in Mediterranean countries. The enhancement of fertilizer and water use efficiency in intensified cropping systems seems to be a key point for boosting crop yields and quality. There is a wide variation related to fertilizer use in Mediterranean countries. Across the last 20 years, some European countries like France, Spain, Italy, and Portugal tend to reduce their consumption of fertilizers by decreasing nutrient application per hectare and enhancing nutrient use efficiency, while in North African and Middle East countries, the rate of nutrients applied to soil continuous to increase (Fig. 2). Regarding fertilizer use in the Mediterranean region, the International Fertilizer Association (IFA) predicts high transformations in the fertilizers market due to the development of new agriculture practices such as high-tech fertigation systems,

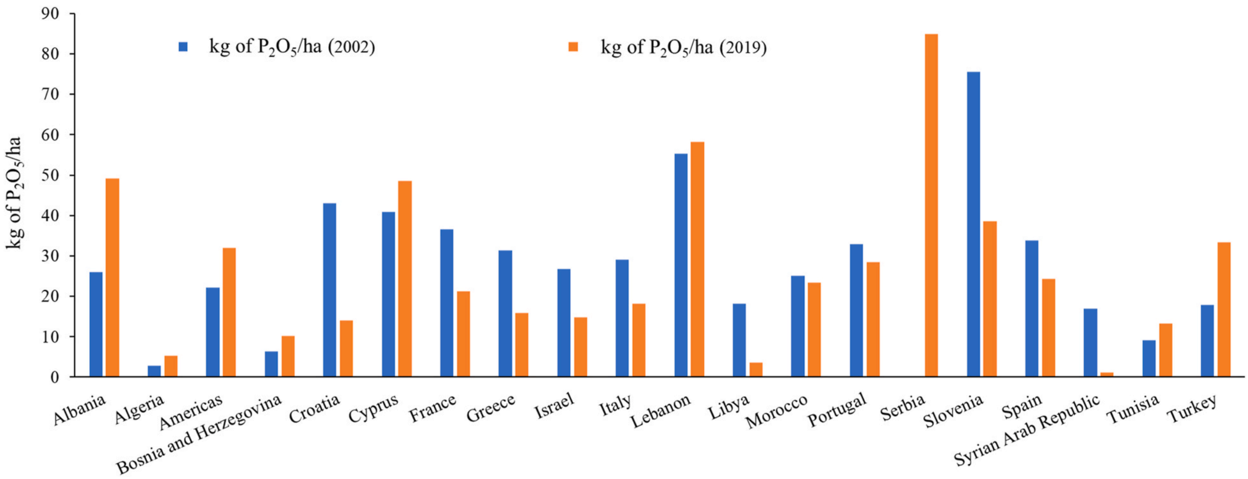

Fig. 2. Phosphorus usage for crop fertilization in Mediterranean countries [19].

horizontal farming as well as hydroponic and other soilless cropping systems. According to the IFA predictions [26], the demand for speciality fertilizers like water-soluble fertilizers (WSF), slow and/or controlled fertilizers, and enriched fertilizers will increase in the next years. It is estimated that the global WSF consumption will increase to 3.6 million tons, and nitrate of potassium (NOP), calcium nitrate (CN), mono-ammonium phosphate (MAP), and mono-potassium phosphate (MKP) will be the most consumed fertilizers around the world.

3. Drip fertigation system: an overview

Drip fertigation is an agricultural practice that has emerged as a new technology to ensure the sustainable use of water and mineral resources. It is defined as a modern agricultural technique for supplying crops with nutrients through a drip irrigation system [27]. With the increased use of micro-irrigation systems, fertigation has become more common, especially in greenhouses, orchards, and vegetable production systems. It offers a good opportunity to optimize crop yield and quality by providing plants with water and nutrients in frequent, uniform, and small quantities directly to the active root zone, considering the plant nutrient requirements during the growing season [28]. Phosphorus drip fertigation was reported to be more efficient in terms of nutrient uptake and crops yield as compared to other P application methods (broadcasting or banding). The main mechanism by which P drip fertigation can improve P availability in soil, plant recovery, and plant growth and yield is the aptitude of P drip fertigation to minimize P loss processes in the soil especially the precipitation and the adsorption of P ions with soils minerals [29]. P drip fertigation consists of the application of small and frequent P rate during the growing season, which limits the time of P fertilizer exposure to soil minerals and improve P availability in the soil and its uptake by plant roots. Moreover, P drip fertigation can easily schedule P application rates to coincide with crop nutrient requirements during the growing season [15].

Indeed, fertigation can improve water and nutrient use efficiency and minimize fertilizer losses. Fertigation can contribute to saving energy, and money, and reducing soil compaction. In some degraded soils, such as sandy soils, especially in dry areas, fertigation can be an effective practice for adjusting crop nutrient deficiencies, enhancing water productivity, and ensuring good yields [30]. Fertigation can also offer the possibility of the co-application of some agrochemical inputs such as bio-stimulants, pesticides, and herbicides. Although fertigation is an efficient technique in terms of water and nutrient use, it has drawbacks in terms of high investment costs and the management expertise required. Fertigation can also lead to some risks such as environmental contamination through fertilizer misapplication [31], insufficient nutrient supply, hypoxia problems due to frequent irrigation, especially in clay soils, salts accumulation in the wetting front and dripper clogging [32,33].

4. Phosphorus fertilizers

Phosphate rock (PR) is the main source of phosphorus on the planet, PR generally exist in old marine deposits in many regions around the world. Phosphate rock deposits are the main raw material used to produce P fertilizer for crop fertilization and nutrition. Unprocessed PR deposits can be applied directly as a source of phosphorus for plants, mainly in acidic soils and wet conditions. However, more than 90 % of the world's PR reserves are treated by different chemical processes, based on acidic reactions, to produce a wide range of soluble P fertilizers [34]. Depending on the process, P fertilizers can have variable chemical and physical properties,

Table 2

Physicochemical proprieties of commercial P fertilizers (adapted from Refs. [30,35]).

P fertilizers	$N–P_2O_5–K_2O$ content (%)	pH	Salt index	Solubility at 20 °C (g/l)	Comments
Simple superphosphate (SSP) Ca $(H_2PO_4)_2$	0-18-0	<2	7.8	Low	Granular fertilizer, unsuitable for fertigation, is widely applied by broadcast or banding
Triple superphosphate (TSP) Ca $(H_2PO_4)2H_2O$	0-46-0	3	10.1	Low	
Mono-ammonium phosphate (MAP) $NH_4H_2PO_4$	11-52-0	4.5	24.3	374	Recommended for neutral to basic soils
Di-ammonium phosphate (DAP) $(NH_4)_2$ HPO_4	18-45-0	7.6	29.2	692	Most popular P fertilizer, applied by broadcast or banding
Mono-potassium phosphate (MKP) KH_2PO_4	0-52-34	5.5	8.4	225	Recommended for daily supply fertigation due to its very low salt index
Di-potassium phosphate (DKP) K_2HPO_4	0-41-54	9	17.4	1600	Highly concentered formula in P and K
Phosphoric acid (PA) H_3PO_4	0-54-0	<2	NA	Highly soluble	Recommended for basic soil, can be used to prevent clogging
Urea Phosphate (UP) $(CO(NH_2)$ $2{\cdot}H_3PO_4)$	17.5-44-0	2	NA	Highly soluble	Suitable for fertigation in neutral and alkaline soil, present a reduced risk of N volatilization
Ammonium polyphosphate (APP) $(NH_4)3HP_2O_7$	10-34-0	6	20.0	Highly soluble	Polyphosphates should be hydrolyzed to orthophosphate form before its uptake by the plant and can be mixed with micronutrients
Potassium tri-polyphosphate (KTPP) $K_5P_3O_{10}$	0-48-52	10	NA	1500	High concerted fertilizer, suitable for fertigation
Sodium hexametaphosphate (SHMP) $(NaPO_3)$ n, $16 < n < 22$	0-70-0	6	High salt index	Highly soluble	Unsuitable for use in saline and sodic conditions

such as water solubility, nutrient content, and ortho- or poly-P form. Table 2 presents some physicochemical proprieties of commercial P fertilizers commonly used in agriculture, and their suitability for drip fertigation systems.

4.1. *Suitability of P fertilizers for drip fertigation*

Water and fertilizer application rate and scheduling in the drip irrigation system are critical issues that need to be optimized to ensure good fertigation system efficiency and avoid clogging problems. Several points related to the preparation of the nutrient stock solution and its injection into the irrigation water must be taken into consideration, including fertilizer solubility in water and their compatibility. It is widely accepted that fertilizer applied through fertigation should be completely water-soluble fertilizer at field temperature (20 °C) to ovoid precipitate formation and dripper clogging. Moreover, fertilizer compatibility is also an important point that greatly affects the efficiency of drip fertigation systems. With regards to P fertilizers, the common P formulas used in fertigation systems are ammonium and potassium phosphate salts, urea phosphate, phosphoric acid, and polyphosphate compounds [35]. These P fertilizers interact in different ways with the salts dissolved in the irrigation solution. It is widely reported that P fertilizer containing P, mainly in the orthophosphate form, cannot be mixed with Ca or Mg fertilizers, because insoluble precipitates such as bi and tricalcium phosphate may be formed in the irrigation solution causing canals and drippers clogging [30]. These precipitates are also formed when the irrigation water contains a high concentration of divalent cations such as Ca and Mg.

Urea phosphate and phosphoric acid are the main P fertilizers used in drip fertigation systems, especially in neutral and alkaline soil conditions. Because of its acidic action, phosphoric acid can be used for cleaning fertigation lines from precipitate and avoiding drippers clogging, and at the same time as a source of P for plant nutrition. Also, polyphosphate fertilizers, which are defined as molecule structures with more than one P atom, seem to be more suitable for fertigation and may even chelate some micronutrients like zinc (Zn) and Fe and make them more available to plants [35,36]. Other phosphate-soluble salts such as monopotassium phosphate (MKP) and monoammonium phosphate (MAP) are also used as P fertilizers in drip fertigation systems, due to their high-water solubility and concentrated nutrient content (Table 2).

4.2. *Orthophosphate vs polyphosphate fertilizers*

Phosphate salts used for drip fertigation are produced from phosphoric acid (H_3PO_4), which is the starting material that reacts with other chemical reagents, such as potassium hydroxide or ammonia. When the orthophosphoric acid reacts with ammonia and potassium hydroxide, the monoammonium phosphate (MAP) and the monopotassium phosphate salts are produced, respectively [37]. The phosphate in these two P fertilizers (MAP and MKP) is present in the orthophosphoric form (phosphate molecules with only one P atom). However, in some cases, polyphosphate molecules may be produced by phosphate industrials and used as a source of P for drip fertigation. Ammonium polyphosphate (APP) is the old poly-P fertilizer used for crop nutrition [38]. The APP is produced from aqueous phosphoric acid and gaseous ammonia at elevated temperatures. In this reaction, water molecules are driven off and orthophosphate molecules begin to link together to form, pyrophosphate (two P atoms), then tripolyphosphate (3 P atoms), until obtaining soluble polyphosphate fertilizers with different structures (branched or cyclic), chain lengths, and degree of polymerization (Fig. 3) [39]. Compared to Ortho-P fertilizers, Poly-P formulas are generally more concentrated in nutrients, highly soluble, stable under a wide temperature range, and can be mixed with micronutrients and other chemical fertilizers [40].

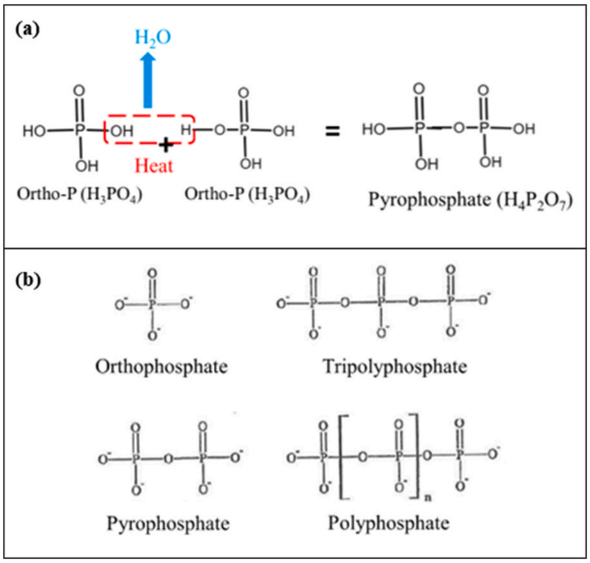

Fig. 3. Production of polyphosphate from orthophosphoric acid (a) and structural formulas for orthophosphate and polyphosphate molecules (b).

Unlike ortho-P fertilizers, which are immediately assimilable by plants after being applied to the soil, poly-P fertilizers must be gradually hydrolyzed into the ortho-P form in order to be absorbed by plant roots [15]. The hydrolysis of poly-P to ortho-P in soil takes time and is controlled by several factors including root exudates, soil microorganisms, soil pH and properties, poly-P fertilizer chemical properties (polymerization rate and degree, chain length), and agronomic practices [15,41]. In general, hydrolysis of poly-P to ortho-P occurs by successively decreasing the degree of polymerization of poly-P to tetraphosphate ($P_4O_{13}^{6-}$),tripolyphosphate ($P_3O_{10}^{5-}$), then pyrophosphate ($P_2O_7^{4-}$), and finally orthophosphate (PO_4^{3-}) [42]. Poly-P hydrolysis is mediated by enzymes produced by soil microorganisms as well as H^+ ions and enzymes secreted by plant roots, such as nonspecific phosphatases [43]. Fig. 4 presents a conceptual model explaining the different behaviors of ortho-P and poly-P forms in soil-plant continuum as well as the main factors governing poly-P hydrolysis in soil.

It has been reported that plants do not respond as quickly to poly-P as to ortho-P in critical phosphorus deficiency, but poly-P are known to have prolonged use by plants [15]. The application of phosphorous fertilizers must consider soil acidity, metal cation content, and soil moisture conditions. Some studies have whown that short-chain soluble polyphosphate fertilizers ($2 < n < 20$) significantly increase soil-available P compared with orthophosphate-based fertilizers such as monoammonium phosphate, diammonium phosphate (DAP), and triple superphosphate (TSP), and improve crop yield and phosphorus fertilizer use efficiency [44].

5. Phosphorus dynamics in soil-plant continuum

5.1. Phosphorus transformations in soil

Phosphorus is one of the most macronutrients that crops need in sufficient quantity to ensure their growth and reproduction functions. It becomes a limiting factor in several cropping systems after water and nitrogen [45,46]. The phosphate ion (HPO_4^{2-} or $H_2PO_4^-$) is the only form that plants can absorb. However, most agricultural lands contain less than 1 mg kg^{-1} of P in soil solution, which is significantly less than 1 % of total soil P [47]. According to Hinsinger [48], P can exist in the soil in different forms: P in soil solution, P adsorbed by the colloids of soil, P in organic compounds, and P in soil minerals. These forms of P differ in their behavior in soil, undergoing major transformation processes that govern P availability for the plant, namely adsorption/desorption, precipitation/dissolution, and mineralization/immobilization [7].

Inorganic phosphorus (Pi) occurs in three main forms: primary P minerals, secondary P minerals, and adsorbed P. In most soils, it is present in very low concentrations in the soil solution, while a large proportion is strongly bound to various soil minerals [48]. Primary P minerals such as apatite are very stable, which means that the release of available P is too slow to meet the crop demand. In contrast, secondary P minerals, which are combined with Al, Fe and Ca, vary in their dissolution rate depending on soil pH and mineral particle size, and can be released through desorption reactions [7]. Phosphorus is generally available to crops the soil pH is ranged between 6 and 7. In acidic soils, P deficiency increases due to strong complexation with Fe and Al oxides. Conversely, in calcareous soils, P retention is dominated by precipitation reactions, but also by the adsorption of P ions on the surface of Ca carbonate and clay minerals [7]. On the other hand, soil organic P (Po) is found as orthophosphate monoesters, such as inositol phosphates, orthophosphate diesters, organic polyphosphates, and phosphonates [49]. P ions can be released from organic P compounds through mineralization

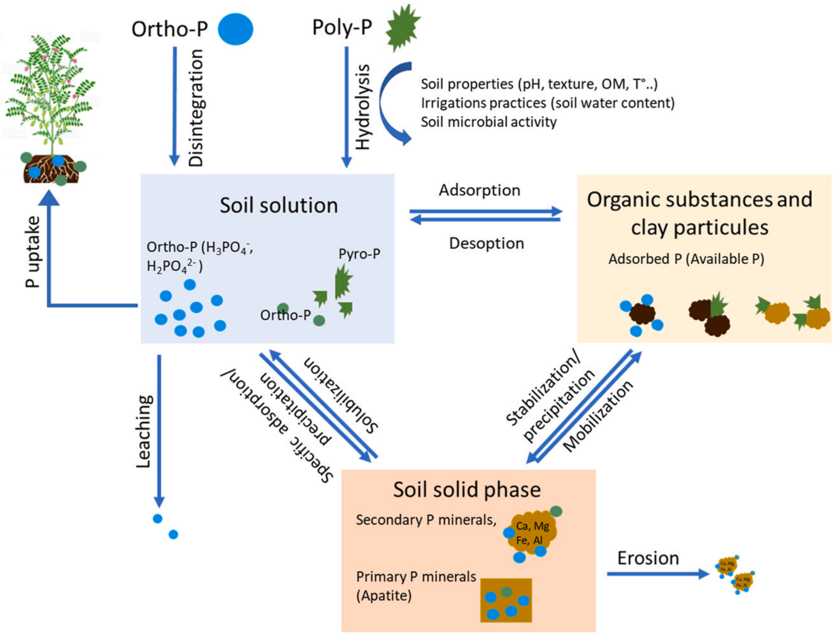

Fig. 4. Conceptual diagram of the Ortho-P and Poly-P fertilizer dynamics in the soil-plant continuum.

processes that are conducted by soil microorganisms and plant roots in association with phosphatase secretion [7]. There are two mineralization processes: 1) biochemical mineralization; it's the process of releasing inorganic ions of P from their organic form via enzymatic catalysis external to the cell membrane, which is strongly controlled by the supply of and needs for the element released rather than the need for energy; and 2) biological mineralization, defined as the release of inorganic forms from organic materials during the oxidation of carbon by soil microorganisms [50].

5.2. Phosphorus uptake and transport in plants

Phosphorus is predominantly absorbed by plants in the ionic form (HPO_4^{2-} or $H_2PO_4^-$) with maximal uptake at a soil solution pH of 5–6. P ions are mainly supplied to plant roots by a diffusion mechanism rather than by mass flow, and are taken up at the root surface by phosphate transporters located in the root plasma membrane [51]. Pi transporters are classified into four families,Pht1, Pht2, Pht3, and Pht4, and are found on the plasma membrane, plastidial membrane, mitochondrial membrane, and Golgi membrane respectively [52]. With regard to the kinetic analysis of P ions uptake, many previous studies have revelated that at low P concentrations surrounding the root surface and under P-deficient conditions, P is absorbed through a high-affinity transporter system with an apparent Km ranging from 3 to 10 μM, however, the low-affinity system is constitutively expressed with Km of 50–300 μM for several crops [53]. Once the P is absorbed by the plant roots, it moves towards the xylem at a rate of 2 mm per hour, then transported to the aerial organs of the plant by symplastic transport against the electrochemical potential gradient, which requires energized transport [53]. In plant tissues, P exists in two main forms: free inorganic orthophosphate (Pi) and organic phosphate ester [54]. Most of the Pi fraction is generally located in the cytoplasm and the excess Pi requirement of the cytoplasm is stored in the vacuole which can act as a buffer to adjust the Pi concentration in the cytoplasm [55]. On other hand, the esterified P pool is mostly involved in the synthesis of nucleic acids, phospholipids, phosphorylated water-soluble metabolites, and phosphorylated proteins, and more than 50 % of the organic P fraction is in the nucleic acids [55]. At the rhizosphere scale (first millimeters of soil surrounding plant roots), several biological and chemical processes occur and greatly induce microscale modifications of the root environment [56]. Such physiological activities include the exudation of organic acids, enzymes, secondary metabolites and sugars by plant roots and soil microorganisms. These changes in the rhizosphere play an important role in P solubilization and uptake by plants and can strongly influence its use efficiency

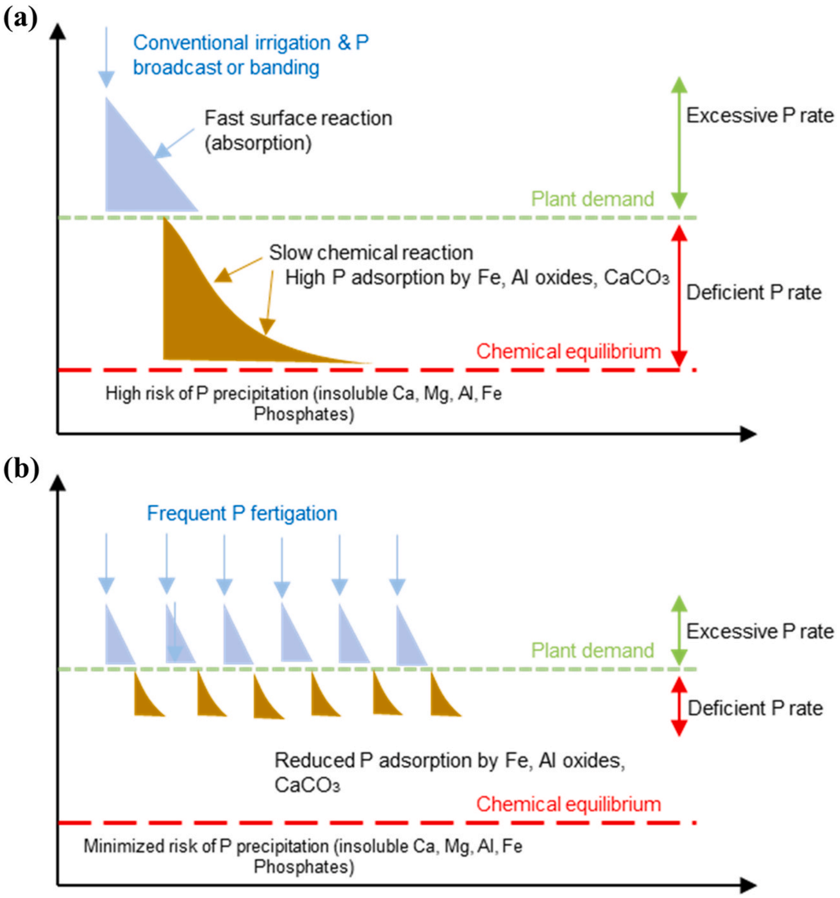

Fig. 5. Schematic presentation of time variation of nutrient concentration in the rhizosphere under conventional (a) and frequent irrigation (b), adapted from Silber et al. [14].

in different agroecosystems [57].

5.3. Phosphorus mobility and availability in soil under drip fertigation

Phosphorus mobility and availability under drip fertigation are mostly influenced by the interaction of several factors including soil edaphic proprieties, climatic conditions, root architecture and exudates, and microbial activity in the rhizosphere [58,59]. It is widely reported that P availability and mobility in acidic or basic soils are very low, this was particularly due to their high P fixing capacity and low P diffusion [60]. Several studies focusing on the dynamic of P under drip fertigation reported that the maximum available P in soil is limited to 0–15 cm of soil depth [61,62]. Compared to other nutrients like nitrates, ammonium, and sulfates, P is less mobile in soil, and its transport and availability are mainly influenced by diffusion mechanisms.

Because of P reactivity and its sensitivity to numerous cations in the soil and irrigation water, a significant fraction of the applied P from drip fertigation is rapidly fixed or precipitated by Ca and Mg cations in basic soils and by Al and Fe hydroxides in acid soils [61]. Thus, P availability depends on pH, Kafkafi, and Tarchitzky [35] reported that P ions distribution between mono and divalent P ions depended on the soil solution pH, it was observed that the monovalent P anion is the dominant P ion below pH 7.2. Several studies have examined the effects of soil texture and organic matter content on P mobility and availability under drip fertigation systems. In experiments carried out by Kirkby et al. [63], phosphorus movement was assessed in contrasting soil textures. As a result, P is more mobile in sandy or coarsely structured soils than in clayey soils. In very sandy soils, P can be leached from the rhizosphere due to the rapid infiltration of water and their low P-sorption capacity [64]. Furthermore, P mobility depended on soil organic matter content, According to Kleinman et al. [64], P mobility in drip fertigation can be improved after organic amendment application and this was particularly due to the role of organic compounds on cations chelation and avoiding P adsorption by soil colloids. In addition to soil proprieties, irrigation practices, particularly the quantity and timing of irrigation, are key factors influencing P mobility in drip fertigation systems. Numerous authors reported that the maintenance of relatively high moisture and frequent irrigation events lead to enhance P mobility and availability in the soil [61,65,66]. It was revealed that a reduction of the time interval between successive irrigations can reduce the variation of P concentration in the root zone and enhance P availability, which significantly modifies root system architecture and growth and improves water and nutrient uptake (Fig. 5). Several hypotheses have been suggested to understand the mechanisms involved in the P dynamic under drip fertigation. Ben-Gal and Dudley [61] studied the impact of two irrigation frequent on P mobility, availability, and P uptake by corn under drip fertigation. As a result, continuous application of water and P fertilizer enhanced the three-dimensional distribution patterns of extractable P (Olsen) by 20–25 % in nearby drippers as compared to intermittent P fertigation applications. Similar results were reported by Elasbah et al. [67] when they studied the impact of two fertigation scenarios (drip irrigation (DI) and subsurface drip irrigation (SDI)) on fertilizer transport using HYDRUS-2D/3D model in tomato plants grown in three different types of soil. This study revealed that SDI was more efficient in terms of water and P mobility and uptake than drip fertigation, especially in medium-textured soils. In long-term experiments evaluating the effect of different irrigation patterns on soil P fractions and availability, Liu et al. [36] demonstrated that total and available P content in 0–60 cm soil profile were higher under surface drip irrigation than subsurface DI and furrow irrigation. This result was mainly attributed to the irrigation amount and frequency that may favor P vertical movement and accumulation.

6. Impact of phosphorus on photosynthesis, crop physiology, and productivity

Plant growth and productivity mostly depend on the photosynthetic activity, carbohydrate synthesis and allocation [68,69]. Phosphorus is involved in several compounds of the photosynthetic machinery and its deficiency in plant tissues causes a remarkable reduction of plant photosynthetic capacity [70]. As the main molecule driving ATP synthesis, inorganic orthophosphate (Pi) is released into the cytosol and involved in the photophosphorylation reactions to produce the ATP from the ADP [69]. Therefore, P is known to be a major regulator of carbon metabolism in plants, and P deficiency can greatly influence the balance between the synthesis and metabolism of carbohydrates [55,71]. Under low P supply conditions, plants exhibit several physiological responses, including reduced leaf surface, reduced photosynthetic rate, and increased root growth [72]. With limited P supply, plants reorient the allocation of carbohydrates to the root part than shoot by increasing root growth, modifying root architecture, and improving root exudates [73,74]. Moreover, plants may also undertake other mechanisms at the cellular level to overcome P deficiency, including the increase of Pi transporters to enhance Pi uptake kinetics, the remobilization of Pi by the homeostatic process by the mobilization of Pi from source organs like vacuole to the chloroplasts, the organelle responsible of the photosynthesis activity [75]. With these adaptation strategies, plants can optimize P use and its allocation in the different plant tissues and overcome the constraints of low P availability in the soil. Also, plants can mobilize the fractions of P that are difficult to absorb through P solubilization mechanism by organic acids secreted by plant roots and soil microorganisms (P solubilizing bacteria and mycorrhizae) which in return improves the photosynthetic P use efficiency, as defined by the instantaneous light-saturated rate of leaf photosynthesis expressed per unit leaf P [57,76].

To explain how P deficiency can affect plants' photosynthesis capacity, several studies were conducted on many crops and authors concluded that substantial non-stomatal inhibition of plants' photosynthesis under P deficiency may be explained by the significant reduction of both ribulose-l,5-bisphosphate carboxylase/oxygenase and ribulose-l,5-bisphosphate regeneration in leaves of low-P-grown spinach and sugar beet [77,78]. Fredeen et al. [79] also revealed that limited P nutrition greatly reduced soybean photosynthesis by the reduction of ribulose-l,5-bisphosphate regeneration due to the reduction of Calvin-Cycle enzyme activity, especially the initial activity of ribulose-5-phosphate kinase and due to the enhancement of carbon flux into starch biosynthesis. One other mechanism explaining the reduction of plant photosynthesis under low P conditions was proposed by Carstensen et al. [80]. The authors have presented a comprehensive biological model in which they attributed this decrease in barley photosynthesis and growth under limited P supply to the disruption of the photosynthetic machinery and the electron transport chain. Under P deficiency, the ortho-P concentration in the chloroplast stroma is reduced to a level that inhibits the ATP synthesis, and accumulation of protons (H^+) in the thylakoids causes lumen acidification which in return reduces linear electron flow between photosystem II (PSII) and photosystem I (PSI). Carstensen et al. [80] revealed that a limited plastoquinol oxidation under P deficiency retards the transport of electron to the cytochrome *b*6f, however, the electron transfer rate of the PSI improved, which increase the NADPH concentration while the ATP synthesis remains limited and consequently the CO_2 fixation.

Regarding the impact of P fertilization on crop growth and productivity, when P is administered to plants through drip fertigation, several studies in the literature have shown beneficial effects of fertigation practices on crop yield, resource-saving, and profitability of cropping systems [35,81]. According to Pan et al. [82], fertigation practices increased crops yield by 7–49 % in tomato (*Lycopersicon esculentum* Mill), sugarcane (*Saccharum officinarum* L.), and improved fertilizer use efficiency in terms of plant nutrient recovery by 15–50 %. A recent study conducted by Chtouki et al. [83] revealed that the adoption of variable rate P application in drip fertigation system significantly increased chickpea yield, quality, and P use efficiency by 12, 9, and 18 % compared to conventional P application strategy. Similarly, for common bean, increased P drip fertigation rates resulted in an improvement of plant vegetative growth, P availability, and nitrogen biological fixation. Moreover, a positive synergy has been widely documented between P and water. Several authors reported that the maintenance of a good level of soil moisture in the root zone increased P mobility into the soil profile, which enhances its availability and plant uptake [45,84,85]. Wang and Zhang [86] suggested that the greater P availability for plant uptake

Table 3
Impact of P fertigation practices on agronomic performances of several crops cultivated in Mediterranean conditions.

Crop species	P fertilizers used	Experimental conditions	Agronomic impacts	References
Corn (*Zea mays (L.)*)	MAP, UP, MKP, PA, SP	2-year field P drip fertigation experiments with tow P application frequencies: high frequency (every 3 days) and low frequency (every 6 days) (Egypt)	High-frequent P fertigation increased P uptake significantly by 12 and 19 % in the first and second seasons respectively, PA and UP yielded better than other P fertilizers (25.67 and 24.5 tons/ha).	[87]
Chickpea (*Cicer arietinum*)	MAP	2-year field P drip fertigation experiments with variable rate P application (Site specific management zones)	Application of P-variable rate fertigation regimes significantly improved P use efficiency, chickpea grain yield, seed quality, and farmer income by 18 %, 12 %, 9 %, and 136 $/ha, respectively, as compared to the conventional drip fertigation practices	[83]
Common beans (*Phaseolus vulgaris* L.)	PA	Field experiment assessed the impact of three P drip fertigation rates (0, 45 and 90 kg P_2O_5 ha^{-1} on bean crop growth and nitrogen fixation performances (Egypt)	Increasing the P application rate enhanced significantly vegetate growth (shoot dry weight by 20 %, root dry weight by 40 %, LAI by 29 %), phosphorus availability (by 46 %), root nodules number (by 83 %) and nitrogen fixation by rhizobia lines	[93]
Chickpea (*Cicer arietinum*)	MAP (ortho-P) & APP (Poly-P)	Drip fertigation experiments with two P fertilizer formulas and three irrigation regimes (adequate irrigation, medium, severe drought stress regimes)	Both P fertilizer forms (orthophosphates and polyphosphates) significantly improved stomatal conductance, photosynthetic activity, biomass accumulation, and nutrient uptake. Soil water content strongly affects P availability and use efficiency (33 and 16 % of PUE of poly-P and ortho-P respectively)	[41]
Wheat (Triticum aestivum L.)	SSP	Three-year field experiments evaluating two P application methods (P broadcasting and P fertigation)	Fertigated P increased grain yield by 12–18 %, P uptake by 4–32 %, agronomic efficiency by 11–20 % and P use efficiency by 2–13 % during three cropping seasons as compared to broadcast method	[29]
Sweet corn *Zea mays (L.)*	PA	A field experiment on corn grown under surface or subsurface emitters, Four P concentrations in nutrient solution: 0.04, 0.16, 0.64, and 1.29 mol m^{-3} (southern Israel)	Increased marketable yield with P concentration, 1.29 mol m^{-3} yielded 26 % better than 0.04 mol m^{-3}, Increased yield (7 %) with subsurface irrigation than on the surface, Increased P in soil solution with high-frequent P fertigation	[65]
Sweet Cherry (*Prunus avium*)	APP (0–34–0)	2 drip irrigation frequency (I1: 4 times daily and I2: 1 time every second day) combined to 2 P application rate (P1: no P and P2: 20 g P/tree) (Canada)	P fertigation enhanced the P concentration of cherry leaves and fruits, No significant impact of water stress on the phenolic compounds of cherry fruits	[94]
Corn (*Zea mays*)	PA	Greenhouse-lysimeter experiments with two fertigation frequencies (4 h once every 2 d, continuous fertigation) (USA)	Continuous fertigation yielded 20 % greater biomass than control and increased P availability in 10 cm of soil depth as well as leaf P content (25 %)	[61]
Wheat (Triticum aestivum L.)	TSP	Field experiment adopting tow P application methods (broadcast before sowing with tow P rates 0 and 100 kg P_2O_5 kg ha^{-1}or at third days after crop emergence by fertigation with three P rates 50, 75 and 100 kg P_2O_5 kg ha^{-1}) (Pakistan)	In high calcareous soil, the P fertigation method was more efficient than broadcast, increased grain yield by 27 %, P uptake by 38 % and P recovery by 87 % compared to a broadcast application	[95]
Corn (*Zea mays*)	SSP, MKP	Pot experiments evaluating the effects of P application methods fertigation or broadcast and lateral depths on the distribution of Olsen-P in soil and yield of maize (China)	Fertigation and SDI improved growth parameters of maize crop (LAI, biomass yield, plant height), P use efficiency, Olsen-P near drip emitters (15 cm of soil depth),	[96]

occurred under high-frequent irrigation events with low water quantity. As seen in Table 3, numerous fields and greenhouse experiments have been carried out to assess the impact of P fertilization through a fertigation system on plant photosynthesis, crop yield, P use efficiency, and water productivity compared to standard P application methods. For example, in a two-year field experiment, Eissa [87] reported that high-frequent P fertigation significantly increased corn P-uptake by 12 and 19 % in the first and second seasons respectively, and phosphoric acid yielded better than other P fertilizers (24.5 t/ha). Indeed, numerous studies focusing on the interaction between P and beneficial microorganisms fixing nitrogen have reported a positive impact of P-efficient fertilization on biological nitrogen fixation processes in legume crops [88–91]. In a meta-analysis, Divito and Sadras [92] showed that P influenced positively the capacity of legumes to fix atmospheric nitrogen. The authors revealed that P is involved in several processes of nitrogen fixation, especially in energy transformation required for the formation and the functioning of nodules, photosynthetic activity, availability of carbohydrates for nodules, oxygen permeability for nodular respiration, adjustment of nitrogen metabolic processes, and oxidative stress mitigation.

7. Phosphorus fertilizers use efficiency

Nutrient use efficiency is one of the most issues that take more consideration in the last few years due to the high pressure on mineral resource used to produce fertilizers and due to the inadequate practices adopted by several farmers [12,55]. Crop and soil scientists elaborated several methods and indices to assess the efficiency of mineral fertilizers used in agriculture. Evaluating the efficiency of nutrient use make it possible to recommend numerous techniques and corrective practices to rationalize the use of fertilizers by farmers and reduce their environmental impacts on the biosphere. The direct measurement of nutrient use efficiency by crops can be evaluated using labelled fertilizers like ^{31}P-labelled fertilizer, in this case, the P use efficiency is calculated as the ratio between direct ^{31}P uptake from the fertilizer and the total ^{31}P supply [97]. In other cases, a difference method is also used to assess mineral fertilizer efficiency. The difference method is generally based on crops yield or nutrient uptake considering a negative control without the applied nutrient. When the crop yield is used in the calculation, nutrient efficiency is called the “nutrient agronomic efficiency (NAE)” and is calculated by equation (1):

$$NAE\ (\%) = \frac{(Y_N - Y_0)}{\mathrm{F}} \times 100 \tag{1}$$

where Y_N and Y_0 are crop yields with and without the nutrient being evaluated, respectively, and F is the amount of fertilizer used in kg ha^{-1}.

However, when the nutrient uptake is used in this difference method, this index is called “nutrient use efficiency (NUE)” and is calculated according to equation (2):

$$NUE\ (\%) = \frac{(U_N - U_0)}{\mathrm{F}} \times 100 \tag{2}$$

Where U_N and U_0 are nutrient uptakes with and without the nutrient being evaluated, respectively, and F is the amount of fertilizer used in kg ha^{-1}.

Other indices can be calculated based on the crop yield and the fertilizer amount, such as the “nutrient partial productivity factor” which is calculated as the ratio of crop yield and fertilizer amount (equation (3)), and the “nutrient physiological efficiency (NPE)” of the applied nutrient which is represented by the increase of crop yield per kg of increase in nutrient taken up (equation (4)).

$$PF = \frac{Crop\ Yield\ (kg)}{Fertilizer\ amount\ (kg)} \tag{3}$$

$$NPE = \frac{(Y_N - Y_0)}{(U_N - U_0)} \tag{4}$$

The efficiency of applied mineral P fertilizers has been estimated to be less than 25 % [13]. The average P use efficiency for cereals, the main crops in the Mediterranean region, was estimated at 16 % for the period from 1961 to 2013. For example, the maximum PUE for spring wheat was estimated at 25 % using labelled ^{31}P [98]. Moreover, for some legume crops such as chickpea and common bean, PUE can reach 40 %, especially when water-soluble P fertilizers are used in drip fertigation system. Generally, PUE efficiency is still very low compared with other nutrients such as nitrogen and potassium, which prompts the scientific community and players in the mining sector to step up their work and promote innovation in this field to rationalize the use of this natural resource, The low P use efficiency may be explained by several factors including soil and fertilizer intrinsic properties, farmer agronomic practices, weather conditions and crop species and genotypes. Soil pH is the main soil property governing P use efficiency, it is well known that when P mineral fertilizer is applied to soil, several reactions take place depending on the source of P and the soil pH [99]. After the application of granular fertilizer, the granule will slowly dissolve P ions in soil water and supply soil solution with ortho-P form until its saturation [100]. Other P reactions may take place depending on soil pH, mineralogy, and organic matter content [101]. Under extreme soil pH conditions, P use efficiency is firstly limited by reduced plant growth [102]. For example, root growth is drastically reduced by aluminium and manganese toxicity in acidic soils, however, in highly alkaline soils, micronutrient deficiencies limit crop growth and consequently reduce P use efficiency [103,104]. Moreover, soil pH directly affects P chemistry and transformation in soils. In acidic soils, P transformations are mainly predominated by adsorption reactions of P ions from soil solutions into the soil solid phase [40].

The greater proportion of P is adsorbed on clay minerals dominated by Al, and Fe oxides. However, in calcareous soils, the retention of P ions is mostly dominated by P precipitation with calcium to form insoluble P minerals [18]. In this regard, the greater P use efficiency is obtained in neutral to relatively acidic soil pH conditions. Soil clays and organic matter content are also known to affect P availability and use efficiency [105]. Soils with high clay content and organic matter generally retain more P than highly sandy soils and soils with very low organic matter, which in return affects P availability and use efficiency [15,59].

Among the chemical and physical properties of P fertilizers, P solubility is the main property that affects P acquisition and use efficiency by crops [34]. Highly soluble P fertilizers like MAP, DAP, TSP, and MKP are the most soluble P fertilizers used as a source of P in many cropping systems around the world [97]. Due to their high-water soluble P content, these fertilizers supply plants with enough P after fertilizer application in soil compared to other less-soluble P fertilizers such as phosphate rock (apatite) or phosphate rock partially acidulated, except in highly acidic soils where phosphate rock may be considered as a slow-release fertilizer and can be more effective for some crops [106]. Another comparison based on the type of P fertilizer (dry granular vs water-soluble P fertilizer) can be made for the analysis of P use efficiency from mineral P fertilizers. Since most P taken up by plants reaches the roots by diffusion in the soil with the soil water phase, the type of P fertilizer can therefore affect P mobility, availability, and consequently its use efficiency. For example, when the dry P fertilizer like TSP or granular MAP is applied to soils, the fertilizer granule is dissolved by soil water which rapidly increases P concentration around the granule and then increases the precipitation of P ions with Ca and Mg to form insoluble P minerals, especially under calcareous soil conditions [107]. Diffusion of P from dry fertilizer may be also drastically reduced due to the drought conditions and low water availability in soils [61]. However, for water-soluble P fertilizer, P diffusion is improved by the high solubility of P water-soluble fertilizer in the irrigation water and by the enhancement of P mobility through the preferential water pathways in the soil, which consequently improves P availability near roots and increases plant P uptake and use efficiency [108,109]. In a recent study, Wang et al. [96] showed that water-soluble P fertilizer (MKP) is more effective than dry P fertilizer (SSP) under a drip fertigation system. The authors attribute this higher PUE of MKP to its capacity to improve P availability in soil (Olsen-P) and due to the uniform P application across plants, with the same nutrient concentration in every drop of fertigation solution, as well as due to the increased mobility of P through the drip fertigation system.

Recently, the Poly-P fertilizers with short polymerization chains have gained more attention as an effective source of P for crops compared to the standard ortho-P fertilizers. Several previous studies showed that Poly-P fertilizers like ammonium polyphosphate (APP) present a high PUE in calcareous soils for many crops [16,110]. The mechanism involved in this improvement of PUE is mostly attributed to the role of slow-release of P from poly-P fertilizer in the enhancement of P availability in the soil and by their capacity to minimize P ions precipitation with calcium in calcareous soils as well as by their ability to chelate micronutrient and enhance their uptake by plants [40,41]. The study conducted by Gao et al. [44] et al. showed that the PUE of the Poly-P (APP) was higher than that of the ortho-P (MAP) showing an increase of 18 %. In addition to the above-mentioned factors affecting PUE, many recent technologies related to the P fertilizer process have emerged to improve P use efficiency. The study conducted by Lombi et al. [18] reported that liquid P fertilizer improved phosphorus mobility and availability compared to granular P fertilizers. This may be explained by: (i) the slow-release properties of the poly-P fertilizers, which move in condensed form in the soil before being hydrolyzed, and it does not interact strongly with soil mineral particles of Fe_2O_3/Al_2O_3 [42,111] (ii) Poly-P can increase the concentration of micronutrient that can be present in the fertilizer solution due to their ability to form metallic-cation multivalence chelate coordination complexes that are more soluble than the salts and oxides of the metals. Likewise, Wang et al. [112] revealed that in calcareous soil, a poly-P fertilizer treatment improved considerably P-availability. Besides, poly-P fertilizer application decreases soil rhizosphere pH value at 0.1–0.5 unit [111]. The P fertilizer can be improved using slow releasers like polymers and humic substances as a coating agent to control the release of P ions, from the P fertilizer granule to the soil solution which can reduce P fixation and precipitation and consequently improve P acquisition and use efficiency [104]. Other additives like nano-hydroxyapatite, superabsorbent, beneficial soil microorganisms (P solubilizing bacteria and mycorrhiza), and pH modifiers can also be used in co-application in soils or in incorporation into P fertilizer to improve P availability and use efficiency by crops [57,104].

Agricultural practices are also a key factor influencing PUE, the P application strategy (application method, rate, frequency, and delivering time) adopted by farmers may greatly impact P mobility and availability in the soil and then plant P uptake and use efficiency [17]. There are many ways to apply P fertilizer, however, some methods are more efficient than others to obtain a good P efficiency. Early soil P fertilization, especially when P fertilizer is placed near the seed, helps to overcome the low soil P availability [7]. When compared to surface broadcasting, early soil P fertilization allows the application of only a fraction of the P required to achieve comparable crop performances. P fertilization methods that encourage early root growth in the plant development cycle, such as seed coating and P placement near seeds, could be particularly efficient at increasing P use efficiency [104]. Nevertheless, P application through high-frequent drip fertigation systems has shown its effectiveness as an innovative and efficient technique to deliver mineral fertilizers for crops through the drip irrigation system [14,85]. P drip fertigation can considerably minimize the exposure time of the added P fertilizer in the soil, reducing P precipitation and increasing its availability for plants and its use efficiency [17,108]. Moreover, foliar P application is also an effective way to administer P to crops, it has been studied in a variety of crops, including soybean, wheat, clover, and corn, and reported to increase photosynthetic efficiency, delay leaf senescence, and increase yields as compared with soil P application [11]. In general, the appropriate timing for foliar P application ranges from canopy closure to anthesis or tasselling to increase growth rate and yield [113]. Although overdosing can cause leaf burn, the detrimental effect depends on the phosphate formulation used. Compared with orthophosphate forms, more P can be added as polyphosphate compounds. It has been noted on corn leaves a maximum concentration of 1.3 % in solutions of tri- and polyphosphates, as compared with 0.5 % orthophosphate, without damaging the plant [114]. Compared with orthophosphates, the application of ammonium tripolyphosphate, followed by ammonium polyphosphate and phosphoryl triamide, was evaluated on maize, and these were determined to be the most effective compounds in preventing damage [113]. Shah and Chu [115] reported that split repeated polyphosphate application was superior to the single application method in increasing P mobility and use efficiency. Also, when P fertilizer is applied in a single basal method, it is easily fixed because of the high P concentration in fertilization placement [116]. In addition, the low water potential of the soil results in an opposition between the direction of water movement and the direction of P diffusion from the P application site to the outside [117]. Therefore, water movement would inevitably block the diffusion of $H_2PO_4^-/HPO_4^{2-}$ [48]. In contrast, when a split repeated method is used for the application of P fertilizers, the concentration of P in the application site is relatively low, therefore the distribution of P in soil is scattering and dispersive [116,118].

8. Future perspectives and challenges to increase PUE in the Mediterranean region

Most of the Mediterranean agricultural systems are facing many challenges related to global warming and climate change impacts on crop productivity and access to water and foods. Drought, soil nutrient depletion, and soil salinity are the most challenging issues of Mediterranean agriculture in the last decades. In this regard, phosphorus drip fertigation was proposed as an innovative technology to improve crops productivity and natural resource use efficiency. The standard methods of P application to soils were showed their limitations especially in terms of nutrient recovery by plants and environmental impact. The development of water-saving technologies has greatly derived the adoption of P drip fertigation by farmers in several cropping systems in the Mediterranean basin. Although P application through irrigation lines can have some limitations, especially in terms of drippers clogging under some specific conditions, water scarcity and the need to optimize P use efficiency have encouraged farmers and manufacturers to find solutions to further promote the adoption of P fertigation practices in Mediterranean conditions. In recent years, several research projects have been carried out on this subject with the aim of understanding the mechanisms by which P drip ferigation can improve water and P use efficiency and crop yields. Moreover, the development of new P fertilizer formulas with higher P use efficiency is also taking more attention in the last years. Among these new P fertilizers, we found the inorganic polyphosphate fertilizers which are considered as slow-release P fertilizers [41]. Some studies revealed that polyphosphate can have the ability to overcome the problem of P precipitation with calcium in drippers and reducing the dripper clogging issues through their capacity to chelate cations and micronutrients, but results remain highly divergent and inconclusive in this respect [41,119]. Moreover, several recent studies on polyphosphate fertilizers have shown that poly-P present a higher agronomic performances and better P use efficiency as compared to standard orthophosphate fertilizers [15,120]. In drip fertigation systems, the poly-P fertilizers have been recommended as adequate source of P for legume crops and their polymerization properties can be used to reduce P application frequency without impacting the yield or its quality. However, some other studies revealed that under drought conditions, the poly-P fertilizers can loss these advantages and their hydrolysis can be drastically reduced which in turn impact crops yield and P recovery by plants [41]. The Poly-P hydrolysis process, which is the main mechanism governing P availability and uptake from inorganic Poly-P fertilizers, is drastically reduced under drought conditions. Knowing that Poly-P effectiveness is highly conditioned by the availability of sufficient water resources for irrigation and hydrolysis processes, the potential use of Poly-P as a source of P for crops under Mediterranean pedoclimatic conditions, strongly exposed to very frequent and sometimes very long periods of drought and water stress, can be questioned. With this regard, we strongly recommended continuing the investigations about the behavior of Poly-P fertilizers under alkaline soils and semi-arid conditions to evaluate the long-term effect of Poly-P fertilizers on phosphorus status in alkaline soils (different pools of soil P: total P, available P, adsorbed P). The impact of the Poly-P residual effect on the following crops and their interaction with crop species and genotypes can also be explored in future research. Moreover, the environmental implications of P fertilizations practices (choice of P forms, rates, and application methods) should be addressed to assess the environmental risks associated with the use of phosphate fertilizers, including the study of phosphate loss processes from mineral fertilizers at large scale and their impact on the sustainability of agroecosystems.

On the other hand, studies currently being carried out on P drip fertigation deal with problems linked to dripper clogging, with a view to understanding how phosphate fertilizer doses and irrigation water quality can impact on the clogging phenomenon. A recent study conducted by Xiao et al. [121], revelated that dripper clogging is closely related to P fertilizer type and calcium content of irrigation water used in the drip fertigation system. This study showed that phosphorus fertilizer reduced emitter clogging at low Ca2+ concentrations, however, at higher Ca content in irrigation water, P fertilizer increased the risk of dripper clogging. Results from Xiao et al., 2020 [119] revealed that urea phosphate fertilizer was the most effective P fertilizer when compared to monopotassium phosphate or ammonium polyphosphate in terms of dripper clogging. The interactions between poly-P forms and other mineral fertilizers could be addressed in future research to evaluate the compatibility of such combinations of nutrient solutions on nutrient availability, crop physiology, crops yield. Furthermore, the impact of poly-P fertilizers on drippers and emitters clogging as well as on the efficiency of drip irrigation systems should be assessed, especially when relatively saline water is used for crop irrigation like in some semi-arid regions. It is also important to note that in the Mediterranean conditions, the use of saline water for irrigation is an agricultural practice often used to overcome the problem of water availability. To this end, the study of the interaction between saline water and phosphate fertigation practices requires more attention and research in the coming years.

To improve P use efficiency under drip fertigation systems, several other approaches and strategies can be developed in the future research, including the use of some microorganisms having the capacity to solubilize the recalcitrant fractions of P in soil as well as the use of root exudates or organic acids and amendments like humic substances and seaweed extracts [57]. The recent development in the production of bioinoculants from soil beneficials microorganisms like phosphate solubilizing bacteria and arbuscular mycorrhiza fungi can greatly contribute to improve P cycle in soil plant continuum and increase its use efficiency. On the other hand, recent innovations in precision farming can also make a major contribution to improving the efficiency of phosphate fertilizer under drip fertigation. As revealed in a recent study conducted by Chtouki et al. [83], the delineation of P drip fertigation management zones of chickpea crop using electromagnetic induction technique and geospatial modeling has greatly increased grain yield, seed quality, and PUE at field scale compared to standard P application methods. In line with this, future research is needed to explore the added value of precision agriculture technologies in terms of crop improvement and natural resource saving under Mediterranean pedoclimatic conditions. The delineation of P fertigation management zones can be improved by the integration of complementary data from the soil, the canopy, and the weather using newly available sensors and techniques. For example, the NDVI evaluated by satellite image or drone camera (hyperspectral and multispectral), as well as the chemical soil fertility assessed by ion selective method or other technologies like NIR spectroscopy and gamma-ray, can be very useful for the delineation P fertigation management zones which can contribute to improve P use efficiency and reduce its negative impacts on the environment.

9. Conclusions

As shown throughout this review, a major part of the Mediterranean countries suffers from water scarcity and nutrient deficiencies in agricultural soils, which negatively impacts the productivity and the sustainability of crop production systems. The high pressure on natural resources especially for essential and nonrenewable resources like water and phosphorus pushes the scientific community and industrials to develop new products, approaches, and technologies to improve water and phosphorus use efficiency. In this context, fertigation has been proposed as an effective technique to overcome these constraints of water shortage and low P use efficiency of mineral fertilizers under Mediterranean conditions. The present study highlighted the main questions related to the use of P fertilizers under drip fertigation systems and the consequent effects of P fertigation practices on crop physiology, productivity, and nutrient transformation in the soil-plant continuum.

Knowing that dry phosphate fertilizers are very reactive in most agricultural soils and their use efficiency is very low, the application of water-soluble phosphate fertilizers via drip fertigation systems can greatly contribute to reducing the fixation and precipitation processes of P with soil cations, through the application of a low dose of P fertilizers at high-frequency scheduling. An overall description of P-fertilizers' suitability for drip fertigation and their consequent impacts on the main plant biophysiological processes like photosynthesis, crop growth, and productivity is reported in this paper. The comparison between orthophosphates and polyphosphates fertilizers as well as their use efficiency and transformations in the soil-plant continuum are extensively discussed. We believe that the fundamental topics and the practical recommendations on P drip fertigation management presented in this review paper will be of great interest to researchers in the agronomic field, farmers, and industrials to improve water and P fertilizers use efficiency under drip fertigation regimes and ensure sustainable productivity of Mediterranean cropping systems.

Data availability

Data included in article/supp. material/referenced in article.

Declarations

Compliance with Ethical Standards: Not applicable.
Consent for publication: Not applicable.

CRediT authorship contribution statement

Mohamed Chtouki: Writing – original draft, Writing – review & editing, Data curation. **Rachida Naciri:** Visualization, Formal analysis, Data curation. **Abdallah Oukarroum:** Validation, Supervision, Resources.

Declaration of competing interest

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

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