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Phosphorus bioavailability of sewage sludge-based recycled fertilizers in an organically managed field experiment

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Abstract

Recycled phosphorus (P) fertilizers from sewage sludge can contribute to the ongoing effort of closing the P cycle. Five recycled P fertilizers (Struvite SSL, Struvite AirPrex®, P-RoC®, Pyrolysis coal, and Na-SSA) were tested for their P availability in a two-year field experiment with maize. The experiment was conducted on an organic certified research station at soil pH 6.5. Other P fertilizer treatments included: phosphate rock (PR), compost, and an unfertilized control. In addition, the rhizobacteria strain *Bacillus sp.* Proradix (Proradix®) was applied to test its ability to increase P bioavailability. Each year, shoot DM and P offtake of maize was measured and P use efficiency of the tested fertilizers was calculated. No significant differences in shoot DM were found among fertilized treatments and the unfertilized control in both years of experiment. Fertilization with recycled fertilizers increased P offtake by between 0% (Na-SSA) and 27.5% (Struvite SSL) compared to the unfertilized control. Rhizobacteria application led to an increase in P offtake of maize from 25.9 to 38.7 kg P ha^{-1} when combined with PR fertilization in the year of fertilizer application, while no significant effect was found for the recycled fertilizers. Some of the tested recycled fertilizers from urban waste water can be considered as effective fertilizers for their use in organic agriculture.

Key words: phosphorus fertilization / phosphorus mobilization / recycled phosphorus / rhizobacteria

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1 Introduction

Over the last decades, discussions on future phosphorus (P) scarcity have led to an increasing debate by governmental institutions, researchers, stakeholders, and farmers about closing the societal P cycles. Agriculture alone accounts for the consumption of approximately 80% of P from phosphate rock (PR) for fertilizer production (*Scholz* et al., 2014). Phosphate rock is a finite resource. The estimated period until full depletion of global PR reserves is subject to strong disagreement and ranges from a few hundred to thousand years (*Chowdhury* et al., 2017). Suggestions to increase societal P use efficiency are an increased recycling rate from urban areas back to arable land, optimized land use, improved fertilizer application techniques, P-reduced livestock diets, breeding towards plants with higher P use efficiency, and application of rhizobacteria to improve P availability and accessibility by plants (*Rodríguez* and *Fraga*, 1999; *Withers* et al., 2014).

Commercially available bioeffector products, which contain spores of living microorganisms, have been developed as inoculants to improve P supply of plants. Mineralization and solubilization of orthophosphate from organic and inorganic soil P is promoted by organic acids and phosphatases that are synthesized by various soil bacteria (*Lavakush* et al., 2013). In addition, a stimulation of root growth leads to an expansion of the root system and thereby an increased volume of accessible P pools in soil (*Jakobsen* et al., 2005). It is widely agreed that *Pseudomonas* strains are among the most effective rhizobacteria to stimulate plant growth (*e.g.*, *Santoyo* et al., 2012; *Miransari*, 2014). *Pseudomonas* sp. are capable of rapid growth and show good rhizosphere colonization due to their ability to use various substrates as nutrients (*Santoyo* et al., 2012), and are promising in terms of P solubilizing (*Rodríguez* and *Fraga*, 1999). *Hameeda* et al. (2008), *Collavino* et al. (2010), and *Kaur* and *Reddy* (2014) particularly describe a P solubilization ability of bacteria strains under supply of insoluble P sources or without additional P fertilization. This leads to the assumption that the P-solubilization ability of bacteria might be enhanced under low P supply or low P availability. Thus, a specific utilization of P solubilizing rhizobacteria could be a promising approach to enhance P availability of less labile soil P forms (*Kaur* and *Reddy*, 2014), especially in organically managed farming systems, where highly soluble P fertilizers are prohibited.

However, true long-term sustainability can be achieved only through a complete recycling of P from waste streams of

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urban areas back to agriculture (*Möller* et al., 2018). Municipal waste water is the largest non-agricultural potential source from which to recover P (*van Dijk* et al., 2016), but direct sludge applications are forbidden in organic agriculture in the European Union. In Germany, direct application of sewage sludge shall be replaced by a P recycling until year 2025. The broad range of different (chemical and thermal) P recycling technologies has been described by *Egle* et al. (2015). Fertilizer efficacy of recycled P fertilizers from urban wastewaters has been tested in many pot experiments (*e.g.*, *Cabeza* et al., 2011; *Wollmann* et al., 2018; *Möller* et al., 2018), but there is a lack of data testing recycled P fertilizers for their bioavailability under field conditions.

Strong P imbalances, negative P budgets, low soil P status, and a long-term subtle depletion of soil P (*Nesme* et al., 2012; *Cooper* et al., 2018) have been reported for different organic farming systems. Phosphorus supply of crops poses a major challenge due to the limitation of permitted P fertilizers and the ineffectiveness of PR and meat and bone meal fertilization in soils with pH > 6.0 (*Guppy* and *McLaughlin*, 2009; *Nesme* et al., 2012; *Möller* et al., 2018). Hence, there is a need for plant-available P fertilizers for organic crop production. The use of recycled P fertilizers from urban areas in organic agriculture perfectly fits with basic organic principles of a closed nutrient cycle and the use of renewable resources (*Seufert* et al., 2017).

The aim of the present experiment was to assess the P fertilizer efficacy of recycled P fertilizers under field conditions. We hypothesized that (1) the P availability of recycled fertilizers is higher compared to PR and urban organic waste compost and (2) the application of the bioeffector product Proradix® leads to an increased plant P offtake compared to treatments without bioeffector applications.

2 Material and methods

2.1 Investigated recycled P fertilizers

The tested P fertilizers were obtained from chemical (Struvite SSL, Struvite AirPrex®, P-RoC®) and thermal processes of P recovery [Pyrolysis coal, sewage sludge ash (Na-SSA)]. Struvite SSL was produced from the liquid fraction of sewage sludge, after a chemical re-dissolution of P in a pilot plant of the Stuttgart Sludge Leaching Process, provided by the Department of Wastewater Management (ISWA, Stuttgart University). Struvite AirPrex® is a commercially available struvite based on the AirPrex® process (Berliner Wasserbetriebe, Berlin). In the P-RoC® process developed by Karlsruhe Institute of Technology (KIT, Karlsruhe, Germany), calcium silicate hydrate pellets are added to the process water which release hydroxide ions and increase the pH to 9–10. Phosphorus is then recovered by crystallization and struvite as well as non-water soluble calcium phosphates (including hydroxyapatite or brushite crystals) are formed (*Berg* et al., 2005). Pyrolysis coal was produced in an oxygen-free atmosphere at 650°C from sewage sludge by Pyreg GmbH (Dörth, Germany) and post-treated with 96% sulfuric acid (2 kg H_2SO_4 kg^{-1} coal) in order to increase its P bioavailability. Sodium-treated sewage sludge ash (Na-SSA) was produced, aiming to gain a fertilizer similar to Rhenania phosphates (*Möller* et al., 2018) in the ASH DEC® process. The tested compost (pH 8.6; C:N ratio 12; organic matter: 368 g kg^{-1}; dry matter: 75.6%; granule size: 0–12 mm) derived from organic household waste residues separated from municipal solid waste (90%) and green waste from garden and landscaping (composting plant Kirchheim unter Teck GmbH, Germany). The total P concentration in recycled fertilizers was (mg P kg^{-1} DM): 233 (Struvite SSL), 223 (Struvite AirPrex®), 76.3 (Na-SSA), 59.5 (Pyrolysis coal), 49.8 (P-RoC®), and 2.40 (Compost).

Control treatments were unfertilized and fertilized with PR. The used PR was a commercially available fertilizer (Naturphosphat P26, Timac Agro, Austria) consisting of soft ground rock phosphate which was ground (< 0.06 mm) and then granulated (4–10 mm). The granule size of the remaining fertilizers ranged between: 0.09 mm (Na-SSA), < 0.125 mm (Struvite SSL), < 0.5 mm (P-RoC®), 0.5–1,5 mm (Pyrolysis coal), 1–2 mm (Struvite AirPrex®) and 0.1–12.0 mm (Compost). In this study, triple superphosphate was explicitly not included as reference fertilizer since it is not allowed in organic farming systems, thus not representing an alternative fertilization to be compared to.

2.2 Experimental setup

A two-year static field experiment was conducted at the organic certified research station Kleinhohenheim of the University of Hohenheim, Germany. The research station is located in Stuttgart, 435 m asl, with a mean annual precipitation of 700 mm and mean annual temperature of 8.8°C. The soil of the trial field was a silty loam soil with pH 6.5 ($CaCl_2$) and (mg kg^{-1} DM) 837 total P (*aqua regia* extraction), 29.9 P_{CAL} (calcium-acetate-lactate extractable P; *Schüller*, 1969), and (% DM) 1.06 carbonates, 31.2 clay, 55.3 silt, and 13.5 sand. According to the official German fertilizer recommendations, the P status of the soil can be classified in the second lowest category “B” (15–30 mg P_{CAL} kg^{-1} soil), indicating a need for fertilization (*Wiesler* et al., 2018).

The experiment was performed from May 2014 to August 2015 with two cultivation cycles of maize (*Zea mays* L. cv. Ronaldinio; KWS Saat) in a randomized block design including four replicates per treatment. Previous crop in 2013 was a one-year grass–clover ley. Plot size was 3 m × 10 m, consisting of four maize rows each. Recycled P fertilizers were applied manually on each plot prior to sowing in May 2014 at a rate of 80 kg P ha^{-1}. Fertilizers were incorporated to a depth of 10 cm using a rotary harrow, and maize was sown at 6 cm soil depth. After emergence, horn meal was applied (70 kg N ha^{-1}) and incorporated into the soil by harrowing. The amount of N applied with the two struvites (Struvite SSL: 9.58 mg N kg^{-1} DM, Struvite AirPrex®: 9.42 mg N kg^{-1} DM) was considered in the N fertilization rate. Compost N (2.40 mg N kg^{-1} DM) was considered 15% plant available (*Möller* and *Schultheiss*, 2014). In October 2014, aboveground maize biomass was harvested using a row chopper. Per plot, 6 m of the two central maize rows were collected for data acquisition. In May 2015, soil tillage was conducted to a depth of 10 cm on the trial field using a rotary harrow. Maize was sown at 6 cm soil depth. No additional P was applied in the second year of the experiment. Nitrogen was applied as horn meal (150 kg N ha^{-1}) as in the previous year. The lower N fertilization rate in 2014 compared to 2015 was a consequence of the supposed residual N supply of the previously grown grass–clover. In August 2015, maize plants were harvested as described before. After each harvest, fresh matter was determined per plot and dry matter (DM) was measured after drying a subsample of plant material at 60°C until constant weight.

2.3 Assessment of the effects of applied bioeffectors on plant P availability

The bacterial strain *Pseudomonas SSL*. "Proradix" (Proradix®, Sourcon Padena, Tuebingen, Germany), containing 6.60E+10 colony forming units (cfu) per g, was applied to four fertilizer treatments (Na-SSA, Compost, PR, and the unfertilized control) to test its ability to increase P bioavailability. A band application was conducted twice in each growth cycle of maize after germination and 2 weeks later. To reach the target concentration of 1.98E+10 cfu per m^2 per application, 9.2 g Proradix® bacteria powder were dissolved in 20 L of water and applied as 5 L into each of the four maize rows of one plot, using watering cans.

2.4 Phosphorus concentration in plant tissue

Dried above-ground plant material of maize was ground using a laboratory disk mill (TS 250, Siebtechnik GmbH, Mülheim an der Ruhr, Germany). Then, an amount of 0.5 g of plant material was weighed into microwave tubes and digested with 5 mL concentrated (65%) HNO_3 and 4 mL H_2O_2 at 210°C for 62 min (*VDLUFA*, 2011). The P concentration was measured colorimetrically (*Gericke* and *Kurmies*, 1952). Phosphorus offtake was calculated from shoot DM and P concentration.

2.5 Calculations and statistical analysis

Apparent phosphorus use efficiency (PUE) was calculated for both years of the experiment according to the following equation:

$$PUE\ (\%) = \left(\frac{Shoot\ P\ offtake\ (fertilizer) - shoot\ P\ offtake\ (unfertilized)}{P\ applied\ with\ fertilizer}\right) \times 100, \tag{1}$$

where *P applied with fertilizer* was 80 (kg P ha^{-1}) in the first year, and "80 – total fertilizer P offtake of first year" in the second year of the experiment.

The field trial was arranged in a completely randomized block design including twelve treatments with four replicates. Two-way analysis of variance (ANOVA) was performed (SAS 9.4) to study the effect of different P fertilizers and bioeffector application and their interaction on DM and P offtake of maize. After finding significant differences, multiple t-test analysis was performed. One-way ANOVA was performed to study the PUE of different fertilizer treatments ($P \leq 5\%$).

3 Results

3.1 Effect of recycled fertilizers on biomass production and shoot P offtake

Shoot biomass production of maize (t DM ha^{-1}) ranged between 15.6 (Compost) and 18.7 (Struvite SSL) in the first year, and 9.9 (PR) and 11.1 (Compost and Struvite SSL) in the second year of the experiment (Tab. 1). Differences in shoot DM among fertilizer treatments were not significant in both years. Shoot P offtake of maize was significantly influenced by applied recycled P fertilizers in the year of fertilizer application, ranging between (kg P ha^{-1}) 25.9 (PR) and 44.5 (Struvite SSL; Tab. 1). No significant differences were found among recycled fertilizers and the unfertilized control treatment. A significant increase of shoot P offtake compared to the PR control was observed in treatments Struvite SSL, Struvite AirPrex®, Pyrolysis coal, and Compost in the first year of the experiment (Tab. 1). In the second year of the experiment, P offtake ranged between (kg P ha^{-1}) 20.2 (Struvite AirPrex®) and 22.9 (Struvite SSL), but differences were not significant (Tab. 1).

3.2 Apparent P use efficiency of recycled fertilizers

Apparent PUE of recycled fertilizers ranged between 0.36% (Na-SSA) and 11.9% (Struvite SSL) in the first year, and between –0.73% (Struvite AirPrex®) and 2.97% (Struvite SSL) in the second year of experiment (Tab. 2). Negative PUE was found for PR in both years of the experiment, and for Struvite AirPrex® in the second year of the experiment. Highest apparent PUE was found for Struvite SSL in both years of the experiment. However, differences among recycled fertilizers were not significant (Tab. 2).

3.3 Effects of applied bioeffectors on plant P availability

Shoot DM of maize was not influenced by bioeffector application in both years of experiment (data not shown). Shoot P offtake in the PR treatment was significantly increased by application of the bioeffector product Proradix® from (kg P ha^{-1}) 25.9 (no bioeffector) to 38.7 (Proradix® application) in the first year of experiment (Fig. 1). This effect could not be repeated in the second year of experiment, when no additional P was applied (data not shown).

4 Discussion

4.1 Phosphorus bioavailability of recycled P fertilizers

Results indicate that there has been some P supply of applied fertilizers to the maize plants (Tabs. 1 and 2). Among the tested recycled fertilizers, struvites showed the highest P ferti-

Table 1: Shoot DM (t ha^{-1}) and shoot P offtake (kg P ha^{-1}) of maize grown in the first and second year of the field experiment after fertilization with different recycled P fertilizers and phosphate rock (PR = Phosphate Rock; Struvite SSL = struvite obtained from Stuttgart Sludge Leaching Process; Struvite AirPrex® = Struvite obtained in the AirPrex® process; P-RoC® = phosphate compounds recovered in the P-RoC® process; Pyrolysis coal = P obtained from pyrolytic treatment of sewage sludge; Na-SSA = Na-treated sewage sludge ash; Compost = organic household waste compost). Data are means of four replicates. SEM = pooled standard error of the mean, LSD = least significant difference with P < 5%. Different letters indicate significant differences between treatments, ns = not significant.

	P fertilizer	Year 1		Year 2	
Shoot DM (t ha^{-1})	Unfertilized	15.8	ns	10.1	ns
	PR	16.3		9.9	
	Struvite SSL	18.7		11.1	
	Struvite AirPrex®	17.6		10.3	
	P-RoC®	17.8		10.9	
	Pyrolysis coal	17.7		10.1	
	Na-SSA	17.5		10.8	
	Compost	15.6		11.1	
	SEM	**1.07**		**0.55**	
	LSD (5%)	–		–	
Shoot P offtake (kg P ha^{-1})	Unfertilized	34.9	ab	20.8	ns
	PR	25.9	b	20.3	
	Struvite SSL	44.5	a	22.9	
	Struvite AirPrex®	41.9	a	20.2	
	P-RoC®	35.5	ab	22.1	
	Pyrolysis coal	40.3	a	21.9	
	Na-SSA	35.2	ab	21.9	
	Compost	40.0	a	22.3	
	SEM	**3.59**		**1.09**	
	LSD (5%)	**10.6**		–	

Table 2: Mean apparent phosphorus use efficiency (PUE) ± standard error (SE) for different P fertilizers tested in the field experiment in years 1 and 2. PUE was determined relative to the amount of applied P (80 kg ha^{-1}) in year 1 and to the amount of residual P in year 2 [applied P minus apparent offtake of fertilizer P in year 1 (reference value)], ns = not significant (P ≤ 5%).

P fertilizer	**Mean apparent PUE (%) ± SE**		**Mean apparent PUE (%) ± SE**		**Reference value (kg P ha^{-1})**
	Year 1		**Year 2**		
PR	–11.33 ± 4.13	ns	–0.62 ± 0.66	ns	80.0
Struvite SSL	11.92 ± 3.32		2.97 ± 0.29		70.5
Struvite AirPrex®	8.75 ± 6.04		–0.73 ± 0.17		73.0
P-RoC®	0.69 ± 3.21		1.60 ± 1.32		79.5
Pyrolysis coal	6.74 ± 2.66		1.53 ± 2.11		74.6
Na-SSA	0.36 ± 3.33		1.40 ± 1.80		79.7
Compost	6.36 ± 8.25		2.00 ± 1.14		74.9

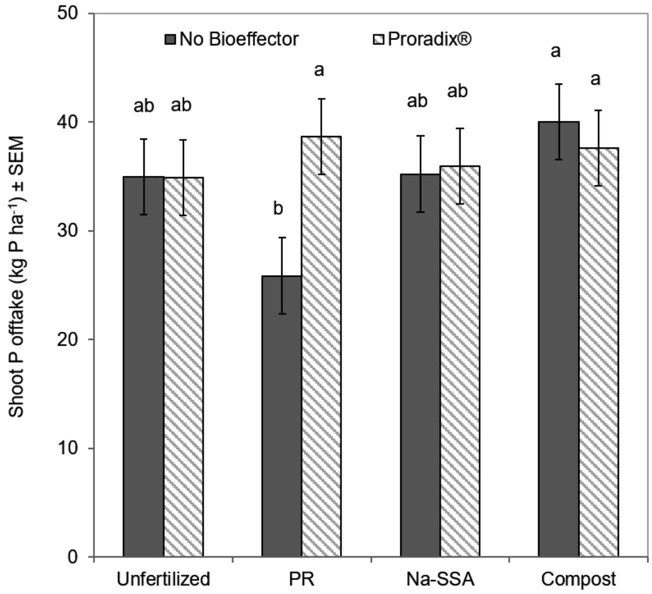

Figure 1: Shoot P offtake (kg P ha^{-1}) of maize grown in the first year of field experiment in various bioeffector treatments and treatments with recycled P fertilizers (Na-SSA = Na-treated sewage sludge ash; Compost = organic household waste compost). Data are means of four replicates, SEM = pooled standard error of the mean. Different letters indicate significant differences among treatments ($P \leq 5\%$).

lizer efficacy, which is in line with *Möller* et al. (2018). The slightly reduced shoot P offtake and shoot DM in the Struvite AirPrex® treatment compared to the Struvite SSL treatment might be caused by a co-precipitation of other P forms (*e.g.*, Ca-/Al- or Fe-phosphates) besides struvite in the AirPrex® process (*Wollmann* et al., 2018). In the SSL process, citric acid is added in order to chelate potentially toxic elements as well as Ca-, Fe-, and Al-ions. *Le Corre* et al. (2005) report a preferential reaction of Ca-phosphates (Ca-P) over struvite crystals when high concentrations of Ca ions are present in the solution. Some Ca-P have low overall plant P availability (*Möller* et al., 2018). Thus, a possibly higher share of non-water soluble Ca-P in Struvite AirPrex® might be the reason for its lower P availability compared to Struvite SSL. *Degryse* et al. (2017) reported a strong effect of particle size on the dissolution rate of struvite and thus on its fertilizer efficacy. Thus, differences in physical shape between both struvites may additionally explain the higher P availability of the very fine-grained Struvite SSL, compared to the coarser Struvite AirPrex®.

Shoot P offtake in the P-RoC® treatment indicates that no additional P had been taken up by maize from this fertilizer, compared to the unfertilized control (Tab. 1). The ineffectiveness of P-RoC® precipitates under the almost neutral test soil conditions (pH 6.5) might be caused by their high portion of hydroxyapatite like compounds (*Berg* et al., 2005), resulting in a low P availability of P-RoC® compared to struvite. Furthermore, there are strong indications that the P fertilizer efficacy depends on soil pH (*Berg* et al., 2005; *Cabeza* et al., 2011; *Möller* et al., 2018). Thus, P-RoC® is a source material for fertilizer production rather than a P-fertilizer itself. Otherwise, unlike struvites, an application of P-RoC® fertilizer is effective only when applied to soils with pH < 5.5 (*Cabeza* et al., 2011).

A few studies have been published on the P fertilizer efficacy of rhenania phosphate-like Na-SSA, highlighting its high P availability and recommending its use in both acidic and alkaline soils (*e.g.*, *Stemann* et al., 2015; *Wilken* et al., 2015). These results are based on laboratory experiments, measuring P solubility in neutral ammonium citrate (*Stemann* et al., 2015) or in greenhouse pot experiments (*Wilken* et al., 2015). These findings could not be confirmed for the Na-SSA when tested under field conditions in our study (Tab. 1). It becomes clear that findings from lab or greenhouse experiments cannot unreservedly be transferred to field conditions, where different external factors might influence the efficacy of a fertilizer. There is a lack of knowledge why the Na-SSA did not show any effect under the present field conditions. Therefore, more field experiments are needed to evaluate the fertilizer efficiency of Na-SSA and its influencing factors.

Although treated with a surplus of concentrated H_2SO_4 (2 kg H_2SO_4 kg^{-1} coal) in order to increase P availability, fertilization with Pyrolysis coal did not enhance DM or shoot P offtake compared to the unfertilized control (Tab. 1). This is possibly caused by its rather coarse particle size. *Mindermann* et al. (2014) reported a high P efficiency of pyrolysis coals produced at 500°C tested at soil pH 6.1. Decreased P availability of the Pyrolysis coal in our experiment might thus be caused by the higher production temperature of 650°C (*Bruun* et al., 2017).

Huge amounts of compost (27 t compost fresh matter ha^{-1}) were applied per plot due to its relatively low P content. Unspecific response to high compost application on plant P offtake has been reported (*Eichler-Löbermann* et al., 2007) possibly through high amounts of sparingly soluble P species such as apatites and octacalcium phosphates contained in composts with a relatively alkaline pH (*Frossard* et al., 2002).

The significantly reduced shoot P offtake in the PR treatment compared to the treatments Struvite SSL, Struvite AirPrex®, Pyrolysis coal, and Compost (Tab. 1) can possibly be explained as an indirect effect of increasing P precipitation and immobilization of soil P by an increase of soil pH caused by the alkalinity of PR (*Sinclair* et al., 1993) or by providing Ca ions into the soil solution. Similar results have been shown in pot experiments (*Wollmann* et al., 2018) for the PR and an SSA treatment, raising issues about the fertilizer efficacy of PR, being one of the few permitted P fertilizers in organic farming. The hypothesis that P availability of recycled fertilizers is higher compared to PR and urban organic waste compost can partly be accepted, showing higher P availability of the recycled fertilizers Struvite SSL, Struvite AirPrex® and Pyrolysis coal compared to the PR treatment, but not when compared with the Compost treatment. Overall non-significant differences in DM and shoot P offtake between fertilized treatments and the unfertilized control in the first year might have been promoted by a residual P supply of the leguminous pre crop (*Nuruzzaman* et al., 2005). Even though there was only 1 year of grass–clover before the experiment started, the crop rotation on this organically managed farm includes legumes in 3 out of 8 years and a generally high contribution of rhizosphere activity and organic matter mineralization to P supply of plants can be assumed (*Mäder* et al., 2002). This assumption is supported by the mean fresh matter yields of maize [52.1 t ha^{-1} (2014) and 38.8 t ha^{-1} (2015)] which are well in line with average silage maize yields in the federal state of Baden-Württemberg, Germany, with 48.5 t ha^{-1} (2014) and 39.3 t ha^{-1} (2015; *Statistisches Bundesamt* 2015; 2016). In the second year of the field experiment, data clearly indicate no residual effect of the P fertilization carried out the year before, even though only a low fraction (up to 11.9% for the Struvite SSL treatment; Tab. 2) of the applied P had been taken up by plants in addition to the soil P in the first year (Tab. 1). Struvite granules dissolve slowly in soil when they are not directly surrounded by roots (*Ahmed* et al., 2015) and the low water solubility might protect struvite-P from being immobilized by adsorption on soil colloids (*Möller* et al., 2018). However, data from our field trial clearly demonstrate that even struvite has a poor residual fertilization effect in the subsequent year, indicating that struvite P is also undergoing the well-known processes of phosphorus aging, transferring the fertilizer P into the less reactive soil P pool (*Bünemann* et al., 2006). The results also indicate that the negative effect of PR on plant P offtake is mainly a short-term effect, lacking any residual effect in the second year after application which might also affect the overall P fertilization strategy. We conclude that fertilizer P should be applied very targeted to responsive crops (*e.g.*, pulse legumes).

4.2 Effect of applied bioeffectors on plant P availability

The response to the Proradix® application was visible only in combination with PR fertilization (Fig. 1). Similarly, *Kaur* and *Reddy* (2014) described the P solubilizing potential of a *Pseudomonas* strain along with PR fertilization in a field experiment, suggesting PR as a proliferation substrate for applied bacteria. This assumption is supported from pot experiments (*Li* et al., 2017) and field experiments (*Kaur* and *Reddy*, 2015) measuring an increased population of P-solubilizing bacteria in soil when *Pseudomonas* inoculation was combined with PR or tri-calcium phosphate. The reported P solubilizing efficacy of bacteria when combined with organic residues (*Thonar* et al., 2015) could not be confirmed from the Compost treatment in our experiment. In general, the reproducibility of the plant growth-promoting effect of bioeffectors is limited (*Thonar* et al., 2017), emphasizing that underlying modes of action are not yet fully understood and being very dependent on environmental conditions, soil substrate, and a combination of various bacterial strains (*Thonar* et al., 2015). The results indicate that biologically active soils have a high intrinsic P mobilization potential and usually no additional effects can be expected from soil supplementation with organisms.

5 Conclusion

The results clearly indicate that the application of recycled P fertilizers show a fertilization effect only in the year of application and no measurable P residual effect in the subsequent year. Therefore, P fertilizers should be applied to responsive crops in the crop rotation. Struvites are the most efficient recycled P source for application in organic farming systems. However, it can be assumed that also struvite P is underlying P aging processes in soil. The high P mobilization potential of biologic active soils makes an application of P mobilizing microorganisms usually rather ineffective.

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