



Bio-based fertilisers can replace conventional inorganic P fertilisers under European pedoclimatic conditions

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ABSTRACT

Mineable phosphorus (P) resources are finite and unevenly distributed globally. Recycling of P from different waste streams as bio-based fertilisers (BBFs) provides a viable option for closing nutrient cycles. To implement this approach effectively, it is necessary to evaluate the P fertiliser efficiency of BBFs under field conditions using a mechanistic approach that links their performance to their chemical composition. This study aimed to test to which extent BBFs can replace conventional inorganic P fertilisers under different pedoclimatic conditions. To this end, the same eight BBFs were tested in field experiments over two consecutive years at five different sites in Europe growing cereals and sunflower. Furthermore, the residual effect of the BBFs in a succeeding crop was investigated. We found that none of the tested P-BBFs resulted in significantly lower yield or total P uptake than triple superphosphate. Ammonium magnesium phosphate (struvite), dicalcium phosphate and phytate-based fertilisers performed best across all field experiments (mean mineral replacement values of 80 – 125 %). No consistent effect of soil or climatic conditions was found. Only marginal residual effects were observed, suggesting that longer trials with repeated applications are necessary to quantify residual effects. The fact that two out of five trial sites were not responsive to P fertilisation highlights the need to consider soil P status for the successful implementation of P fertiliser field trials as well as for fertilising recommendations. In conclusion, most tested BBFs have the potential to replace conventional inorganic P fertilisers across a range of European soils and climate.

1. Introduction

Phosphorus (P) is an essential plant nutrient, and mineable P deposits for production of inorganic P fertilisers are finite and concentrated in a few countries (Chowdhury et al., 2017). Therefore, closing nutrient cycles and achieving a circular economy (CE) is especially important with respect to P recycling (Chojnacka et al., 2020). An analysis of P

flows in Europe indicated a large dependency on P imports coupled with P accumulation in agricultural soils leading to negative environmental effects, little recycling except for manure, and low P use efficiencies (Van Dijk et al., 2016). Based on a re-analysis of Olsen-P-values in European agricultural soils, Recena et al. (2022) suggested that most of the European demand for P could indeed be covered by recycling P from manure, wastewater, and municipal solid waste. This would largely

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eliminate requirements for additional P inputs from mined deposits and hence reduce dependency on countries owning mineable P deposits.

In the past decade, new bio-based fertilisers (BBF) have been developed to replace conventional inorganic fertilisers in agriculture. According to [Wester-Larsen et al. \(2022\)](#), BBFs can be defined as “materials or products derived from biomaterials (plant, animal, or microbial origin, often wastes, residues, or side-streams from agriculture, industry, or society) with a content of bioavailable plant nutrients suitable to serve as a fertiliser for crops”. The new Fertilising Products Regulation (FPR) ([EU, 2019/1009](#)) provides a legal framework for trading BBFs. The classification of CE-marked fertilising products into product-function categories (PFC) provides a characterisation of their function (e.g. fertiliser, liming material, soil improver etc.) and physical state (e.g. solid organic, liquid inorganic etc.), while the origin and/or treatment process of the material (e.g. food industry by-products, animal by-products, composting, digestion, thermal oxidation etc.) is indicated by the component material categories (CMC). These categories, however, do not give a direct indication on the P forms present in the product and consequently on the fertilising efficiency of BBFs. Importantly, there is a general lack of knowledge where, when and how to best apply a given BBF to maximise P use efficiency and minimise losses to the environment, similar as for N-BBFs ([Müller et al., 2024](#)).

As for any other newly developed fertiliser, the fertilising efficiency of BBFs presumably differs depending on soil conditions, as they contain different P species which are known to have variable P availability depending on soil conditions (such as pH, Fe oxides or carbonate content). For example, the plant availability of struvite based P-BBFs decreases with increasing pH, because the thermodynamic stability of struvite is highest at alkaline pH ([Hertzberger et al., 2020](#)). Similarly, the fertiliser performance of hydroxyapatite and iron phosphate has been reported to depend on soil pH, with apatite-based fertilisers primarily solubilizing under acidic soil conditions ([Brod et al., 2015](#); [Christiansen et al., 2020](#)), while iron phosphate-based fertilisers are more available under alkaline conditions ([Kratz et al., 2016](#); [McLaughlin et al., 2011](#)). Given these known interactions of P species and soil properties, testing the fertilising efficiency of BBFs under different soil conditions is necessary. Often, the fertilising efficiency of recycled P products has been evaluated in pot experiments (e.g. [Cabeza et al., 2011](#); [Brod et al., 2015](#); [Ylivainio et al., 2021](#); [Duboc et al., 2022](#)) and less frequently in field trials, as reviewed by [Möller et al. \(2018\)](#) and [Kratz et al. \(2019\)](#). While pot experiments allow for screening of a larger number of BBFs, field experiments operate at a spatial scale that is relevant for agronomic practice and are likely more suitable to reflect the effects of a naturally developed soil profile and its biology (e.g. mycorrhiza, mesofauna, etc.), realistic climate conditions as well as prolonged reaction times between fertiliser and soil, including residual effects to subsequent crops.

To ensure that BBFs are used in a way that optimizes their potential as alternative P fertilisers, their efficiency relative to conventional inorganic fertilisers needs to be evaluated. For practical recommendations, this evaluation should be carried out under field conditions with differing pedoclimatic conditions and with a variety of products of different nature. Results should be explained on the grounds of the contained P forms in the BBFs and how these forms interact with different soil types. This will allow to establish more robust and generalizable recommendations for efficient use of P-BBFs. The objective of this study was to evaluate the short-term and residual P fertilisation effect of current and emerging BBFs for relevant crops grown in Europe under various soil and climatic conditions. To this end, field experiments with the same eight BBFs were conducted over two consecutive years at five sites in Northern, Central and Southern Europe with a similar crop

rotation that included cereals, maize and sunflower. Specifically, the aims were to (i) determine the apparent P use efficiency (aPUE) and the mineral replacement value (MRV) of these BBFs, (ii) examine the effect of pedoclimatic conditions on BBF performance, and (iii) determine the residual effect of the BBFs in the year after fertiliser application. With this, the following hypotheses were tested: (i) there are BBFs that have the potential to fully replace conventional inorganic fertilisers as P source for crops, achieving comparable yields and P uptake in the year of application, (ii) the fertilising efficiency of BBFs is affected by an interaction between their chemical composition and pedoclimatic conditions, and (iii) BBFs containing P species with a slow release pattern will have a low efficiency in the first year, but will lead to a significant residual effect in the succeeding crop.

2. Material and methods

2.1. Design and set-up of field experiments

The fertilising efficiency of P in current and emerging BBFs under various soil and climatic conditions was tested at five sites across Europe, spanning from Spain in the south to Finland in the north ([Table 1](#)). Monthly average temperature and monthly sum of precipitation were obtained from the nearest weather station for each site for the two experimental years (for detailed information on weather conditions during the experimental trials see [SI Fig. 1 – SI Fig. 6](#)). It was targeted to choose fields with low soil P test values in order to get measurable responses to P fertilisation. Nonetheless, the trial in France turned out to be non-responsive to P fertilisation. Similarly, also in the Hungarian trial non-responsive conditions were encountered. Therefore, the trial was repeated at another location one year later. The results from both non-responsive sites were not considered for evaluation of the performance of the BBFs, but the data can be found in the [supplementary information \(SI Figure 7, SI Figure 8\)](#). In addition, insights gained from these experiments on the effect of soil conditions on the general performance of fertilisation trials are included in the main manuscript.

On all fields, a two-year crop rotation was established, with the first crop being either winter wheat, maize or spring barley, and the second crop a cereal at all trial sites except in Spain, where sunflower according to local practice never receives direct fertiliser applications and therefore testing the residual effect on sunflower is highly relevant ([Fig. 1](#)). The crops were chosen according to their local relevance at the different sites, while for comparability at least one cereal crop was included at all sites. Field trials were set up in December 2020 in Spain and in spring 2021 in the other countries.

Across all sites, the same eight BBFs were tested at a standard rate of 30 kg P ha⁻¹ (except in the field trials in France and Spain, where the standard rate was 20 kg P ha⁻¹, following local fertilisation recommendations). Reference treatments fertilised with triple superphosphate (TSP) at 0, 25, 50, 100 and 200 % of the standard rate were established as well. All fertilisers were broadcasted on the soil surface before sowing and incorporated into the topsoil by ploughing or harrowing shortly after application. To ensure that P was the only growth limiting nutrient, all other nutrients, especially nitrogen (N), potassium (K) and sulphur (only at the trial in Finland) were supplemented in sufficient high and equal amounts in all treatments (“blanket application”). The experiments were arranged in a complete randomised block design with four replicates. The plots (minimum plot size: 6 m x 6 m) were split in the second year for the determination of the residual effect on one half of the plot and a second application of BBFs and TSP (equal amount as in previous year) on the other half.

2.2. Selection and characteristics of BBFs

The BBFs were selected with the aim to include chemically diverse products that represent a range of PFCs and CMCs, as defined by the EU Fertilising Products Regulation (2019/1009). The eight P-BBFs tested in the field trials were a sub-selection from a total of 41 P-BBFs described in the LEX4BIO project, of which 30 P-BBFs were also tested in pot experiments (Hernandez-Mora et al., 2024). The main selection criterion for the BBFs tested in the field experiment was their availability in the quantities required for the field experiments (Table 2). The amounts required for all field trials were sourced jointly and shipped to the respective partners conducting the field experiments, so that all experiments were done with the same batch of a given BBF. Chemical characterization of the BBFs was done as described within Section 2.4.

2.3. Soil and biomass sampling

At the beginning of the experiment, soil samples from the plough layer (i.e. top 20, 25 or 30 cm) in each block (i.e. four composite samples containing 20 soil cores each) at each location were collected and analyzed for basic soil characteristics (Table 3). The applied methods are detailed below (Section 2.4).

The aboveground crop biomass was harvested manually at maturity and separated into harvestable yield and vegetative parts. Both fresh and dry weight after drying at 55–65 °C to constant weight of both parts were determined. For cereals, grain yield was also determined using a combine or plot harvester. Subsamples were taken for further analysis.

There were some deviations from the original plan in terms of assessing grain yields. The maize crop in Austria in 2021 was affected by the incidence of the Multiple Ears on a Single Ear Shank Syndrome (MESS) (“bouquet ears”) on the crop, resulting in very poor and variable grain yields. Likely, this phenomenon was caused by an interaction between the chosen maize hybrid (Pioneer P8307) and cold weather conditions during the critical growth stage. The Hungarian trial was affected by severe drought and as a result no maize grain could be harvested in 2022.

2.4. Laboratory analyses

For chemical analyses of the BBFs, a subsample of the BBFs was dried at 37 °C and ground to 1 mm. Total P was analysed after *aqua regia* digestion with ICP-OES (Perkin Elmer Optima 8300). Total organic C (TOC) was determined by dry combustion in a solITOC instrument (Elementar Analysensysteme GmbH). For assessing the P extractability of the fertilisers, a neutral ammonium citrate (NAC) extraction was carried out adapting the BS EN 15957:2011 method (for further details see Hernandez-Mora et al., 2024). The extracts were filtered, acidified and the P concentration in the extracts was measured with ICP-OES (Perkin Elmer Optima 8300). X-ray absorption near-edge structure (XANES) spectroscopy was used to characterize the P species in the fertilisers (Hernandez-Mora et al., 2024). The analysis was performed at the Canadian Light Source (Saskatchewan, Canada) in the autumn of 2021. Due to the high P concentrations, which attenuated spectral features (Gräfe et al., 2014), only the major P species for every fertiliser could be determined and no relative quantification of P species was possible.

Soil samples from the field experiments before fertiliser application were analysed for basic soil characteristics. Soil texture was analysed using sedimentation analysis or by the pipette method (Smith and Mullins, 1991). Soil pH was determined both in H₂O and in 0.01 M CaCl₂ suspensions. The concentrations of total carbon (C) and nitrogen (N)

were measured with a CN Elemental Analyzer (Dumas Method). For calcareous soils, the CaCO₃ content was determined on a Scheibler apparatus. Soil organic C (SOC) was calculated as the difference between total C and C originating from CaCO₃, which was considered to be equal to total C for non-calcareous soils. Total P was measured by ICP-OES after *aqua regia* digestion. For the analysis of available P, the bicarbonate-extractable P, i.e. Olsen P (Olsen, 1954), was used as a standard method.

Biomass samples were milled and analysed for N (CN analyser, Dumas method) and P concentration. For P analysis, samples were prepared either by dry ashing and acid extraction (Spain) or wet digestion with concentrated HNO₃ (all other sites). The determination of P was done through colorimetry using the molybdate blue method (Murphy and Riley, 1962) (Hungary, Spain) or by ICP-OES (Austria, France, Finland). To ensure comparable results between analyses performed at different institutes, a common reference plant sample was distributed and analysed along with the samples.

2.5. Calculations

Different indicators were used to express the agronomic P efficiency of the BBFs. These indicators were only calculated for the fertilised subplots, but not for the residual subplots.

The apparent P use efficiency (aPUE) was calculated as:

$$aPUE [\%] = \frac{P_{uptake_{BBF}} - P_{uptake_{pref0}}}{P_{added}} \times 100$$

where $P_{uptake_{BBF}}$ refers to P uptake in total plant dry matter in treatments fertilised with the BBF while $P_{uptake_{pref0}}$ refers to the mean of the control treatment without any P addition. P_{added} is the amount of added P with the fertilisers in the respective year.

Additionally, the mineral replacement value (MRV), indicating the relative effectiveness of the BBFs compared to the mineral fertiliser reference, was determined as:

$$MRV [\%] = \frac{P_{uptake_{BBF}} - P_{uptake_{pref0}}}{P_{uptake_{pref100}} - P_{uptake_{pref0}}} \times 100$$

$P_{uptake_{pref100}}$ indicates the P uptake in the TSP reference treatment with equal P application rate as the BBFs. All numbers are given in kg P ha⁻¹. The total uptake of P was calculated as the sum of dry matter of the harvestable grain and vegetative plant parts, each multiplied by their respective P concentration.

For assessing the yield response to increasing levels of P fertilisation, the non-linear Mitscherlich type yield response curve was established for the TSP reference samples. Further details can be found in the [supplementary information](#).

For relating the agronomic P efficiency of the BBFs to the local soil conditions, Olsen P values measured before the start of each trial were compared to critical soil threshold values. These threshold values (y) were calculated according to Recena et al. (2022) as

$$y = 49 - 0.016 \times clay - 3.81 \times pH_{H_2O}$$

with clay content given in mg kg⁻¹.

2.6. Statistical analysis

Data preparation and statistical analyses were performed using R (Version 4.2.1) (R Core Team, 2022). A significance level of $p < 0.05$ was used throughout. Model validation, i.e. compliance with the normality and variance homogeneity assumptions, was performed by

visual examination of residual plots.

Statistical analyses were run as linear mixed effect models (*lmer*) within the *lme4* package (Bates et al., 2015). The *emmeans*-package (Lenth et al., 2023) was used for pairwise comparisons, with p-values adjusted for multiple comparisons using the Tukey method.

First, grain yield and total P uptake were analysed separately per location, year and subplot. Considering the randomised complete block design of the individual trials, fertiliser treatment was considered as fixed effect, while block was introduced as random factor. For the second year, a separate analysis was performed for the residual and the fertilised subplots. As the field trial in Finland was arranged as a resolvable row-column design, additional random factors for row and column within the blocks were included.

In a second step, a joint analysis of fertiliser performance across locations was intended. However, this analysis turned out not to be meaningful, since too many data points had to be excluded (i.e. non-responsive conditions in the trials in France and Hungary (1st trial); bouquet ears in Austria in the first year; drought in the first year in Hungary (2nd trial)), leaving only a reduced data set with low statistical power. Furthermore, since different crops were grown at the different locations and in the two years, the effect of location was confounded with the effect of the crops and the year (see Fig. 1), which must be considered for the interpretation of the results.

Instead, the relative estimates MRV and aPUE were used to compare across different locations. Due to the large data variability in the field experiments, determining meaningful estimates for MRV and aPUE was difficult and often resulted in negative values, where yield and P uptake were similar or even higher in the unfertilised control compared to the fertilised treatment. Therefore, data for these indicators was not analysed statistically.

3. Results

3.1. Grain yield and total P uptake at the individual field trial sites

Grain yield and total P uptake differed between the trial sites and years, which was partly due to some extreme weather events. Therefore, results are presented individually per site. The results for the non-P-responsive sites in France and Hungary (first trial) can be found in SI Figure 7 and SI Figure 8.

Austria: The maize crop in the first year had very low and variable grain yields due to “bouquet ears” and no significant differences between treatments were found (Fig. 2). Nonetheless, total biomass production of the maize plants including vegetative parts was less affected and total P uptake in the first year reached high levels ($>60 \text{ kg ha}^{-1}$) (Fig. 3). In the second year, four (BA1, CGO, ADC, OPU) out of eight tested BBFs resulted in a significant yield increase compared to the control. MO14 was the fertiliser with the lowest grain yield and total P uptake and differed significantly from some of the BBFs with the highest performance (BA1, CGO for grain yield; ADC for total P uptake). None of the BBFs had a significant residual effect on the grain yield nor P uptake of winter wheat.

Finland: Yield levels of spring barley were much lower in the first year than in the second year due to drought, and there were no significant treatment effects in year 1 (Fig. 2). In the second year, most BBFs tended to enhance grain yield and total P uptake, especially BA1, OPU and EPH, but differences were only significant for grain yield of OPU (Fig. 3). No significant residual effect could be detected, although for OPU the difference to the control was just not significant ($p = 0.056$).

Hungary: Since in the first field trial there was no yield response to P fertilisation (SI Figure 9), a second experiment was started with maize as first and winter wheat as second crop. However, due to drought, no

maize grains could be harvested in the first year of this second field trial. Grain yield of winter wheat in the second year did not show any differences between treatments (Fig. 2). Total P uptake in the second year tended to increase with increasing levels of TSP and with BBF application, but differences were not significant (Fig. 3). Similar to the trial in Austria, no significant residual effect on yield or total P uptake could be detected.

Spain: Winter wheat yields in Spain were low, both in the first year, reaching less than half of the yield level in Austria, and even lower in the second year as the result of a severe drought (Fig. 2). In the first year, grain yield remained below the level reached with the TSP 100 % reference treatment for all BBFs, albeit non-significantly. In the second year, especially MO14 and OPU tended to increase grain yield of winter wheat. For most BBFs (CGO, ADC, OPU, EPH, and PLA), sunflower yield showed an increasing trend (residual effect), with the residual effect of EPH increasing yield significantly compared to the control. Total P uptake showed a similar pattern as grain yield, but did not differ significantly between fertilisers in both years, except for a significant residual effect of EPH compared to the control without P fertilisation (Fig. 3). Noteworthy, although grain yields of winter wheat in Spain were less than half of the yield achieved in Austria, total P uptake was similar at both sites, at least in the first year. In fact, P concentration in winter wheat straw was about twice as high as at the other locations, indicating that drought might have hindered grain development, but not P uptake in an earlier growth period (data not shown).

Overall, yield responses to P fertilisation remained low at most sites and even the control and TSP 100 % did not differ significantly from each other, although a positive yield response could be observed at those sites that were considered for evaluating the BBF performance (SI Figure 10–14). In contrast to TSP 100 %, some BBFs differed even significantly from the control. In summary, none of the BBFs differed significantly from the TSP 100 % reference in terms of grain yield or total P uptake at any of the sites.

3.2. Phosphorus use efficiency and mineral replacement values of BBFs

The aPUE values for individual sites ranged from -1 to 41 % and the MRV values from -26 to 237 % (Fig. 4, Fig. 5). Negative values are related to small differences between fertilised and unfertilised plots and the high variability of the data at some of the sites. Averaged over all locations, BA1, CGO and OPU had the highest aPUE (Fig. 4, black bars). Also, the average MRV of these fertilisers was highest and even slightly exceeded 100 % in the case of OPU (Fig. 5). On the other side, MO14 and PLA had the lowest aPUE (5 – 7 %) as well as the lowest MRV (43 – 54 %).

Relating the average aPUE and MRV to the dominant P species (Table 2) revealed that especially the struvite (CGO) as well as the dicalcium phosphate type fertilisers (ADC, OPU) had good performances (Fig. 6). Also, the phytate-based fertiliser BA1 was amongst the three best performing BBFs tested across field experiments.

3.3. Relationship of soil P status and agronomic P efficiency

Olsen P values at the beginning of the field experiments ranged between 4.2 and 34.3 mg kg^{-1} (Table 4). In order to predict a yield response to P fertilisation at a given site, critical soil threshold values as proposed by Recena et al. (2022) were calculated based on the clay content and the $\text{pH}_{\text{H}_2\text{O}}$ value measured upon the initial soil sampling. The measured Olsen P values at the beginning of the experiments were markedly below the critical soil threshold value only at the field sites in Austria, Finland and the site of the second trial in Hungary. This observation coincides with a yield response to P fertilisation both at the trial site in Austria and in Finland (SI Figure 10, SI Figure 11), while for

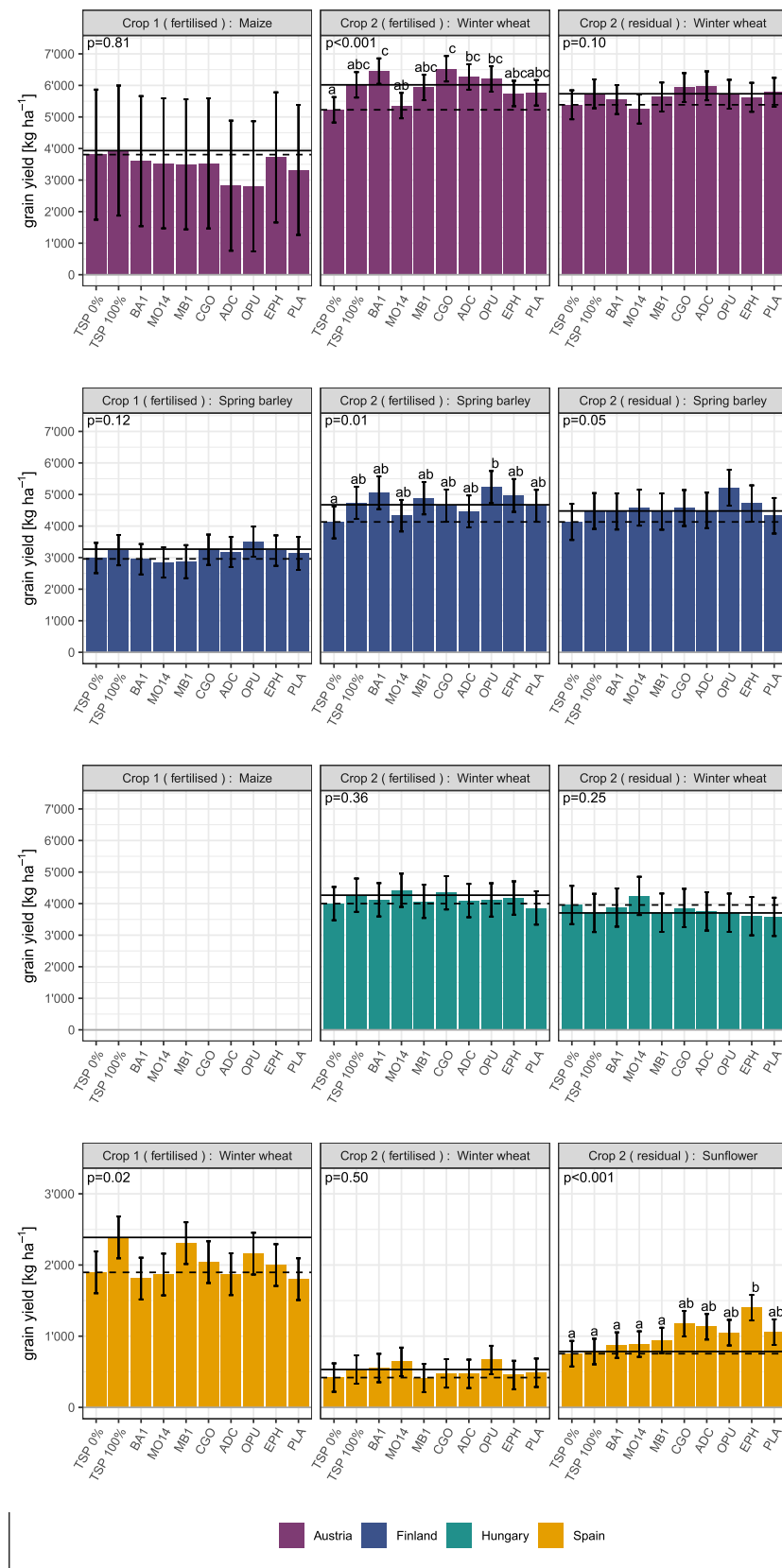


Fig. 2. Grain yield [kg ha⁻¹] in the field trials in Austria, Finland, Hungary and Spain. Bars show estimates with 95 % confidence interval. Black lines indicate the yield level of the TSP 100 % reference treatment, while dashed lines show the grain yield of the control (TSP 0 %). Different letters indicate significant differences between fertilisers ($p < 0.05$) within each location, year and subplot; if no letters are shown, none of the pairwise comparisons between fertiliser was significant. Note the different scale of the y-axis for the trial in Spain. In Hungary (Crop 1, fertilised) no grain yield could be obtained due to drought.

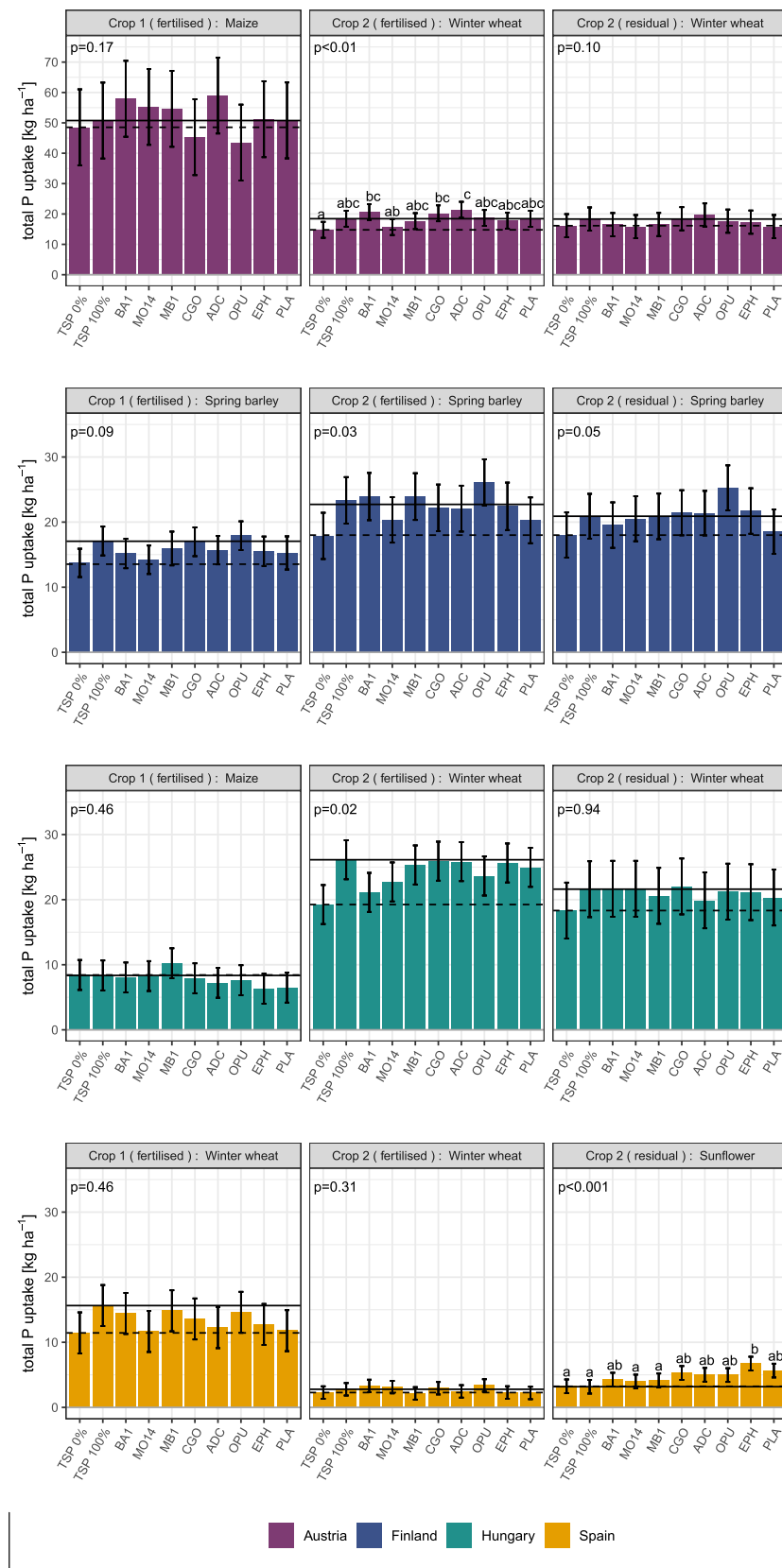


Fig. 3. Total P uptake in harvested aboveground biomass [kg ha⁻¹] in the field trials in Austria, Finland, Hungary and Spain. Bars show estimates with 95% confidence interval. Black lines indicate the total P uptake in the TSP 100% reference treatment, while dashed lines show the P uptake of the control (TSP 0%). Different letters indicate significant differences between fertilisers (p < 0.05) within each location, year and subplot; if no letters are shown, none of the pairwise comparisons between fertiliser was significant. Note the different scale of the y-axis for the trial in Austria.

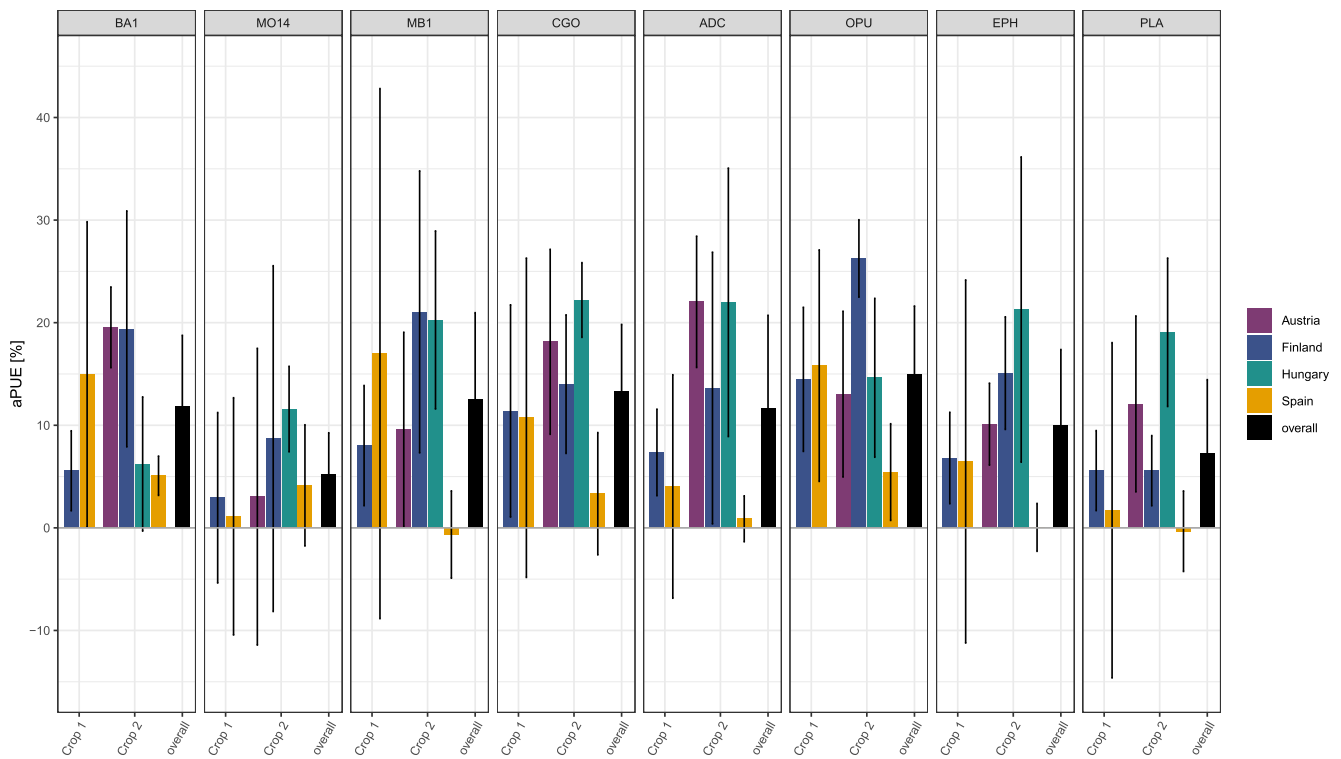


Fig. 4. Apparent P use efficiency (aPUE) of the eight BBFs tested at each of the locations for the fertilised subplots. Data represents mean \pm standard deviation ($n = 4$). Overall mean was calculated from the mean values of the individual countries. Data for France and Hungary (first trial) were excluded due to non-responsive conditions. Data from the first year in Austria and Hungary (second trial) were excluded since grain yield was strongly affected by disease (Austria) or no grain could be harvested (Hungary).

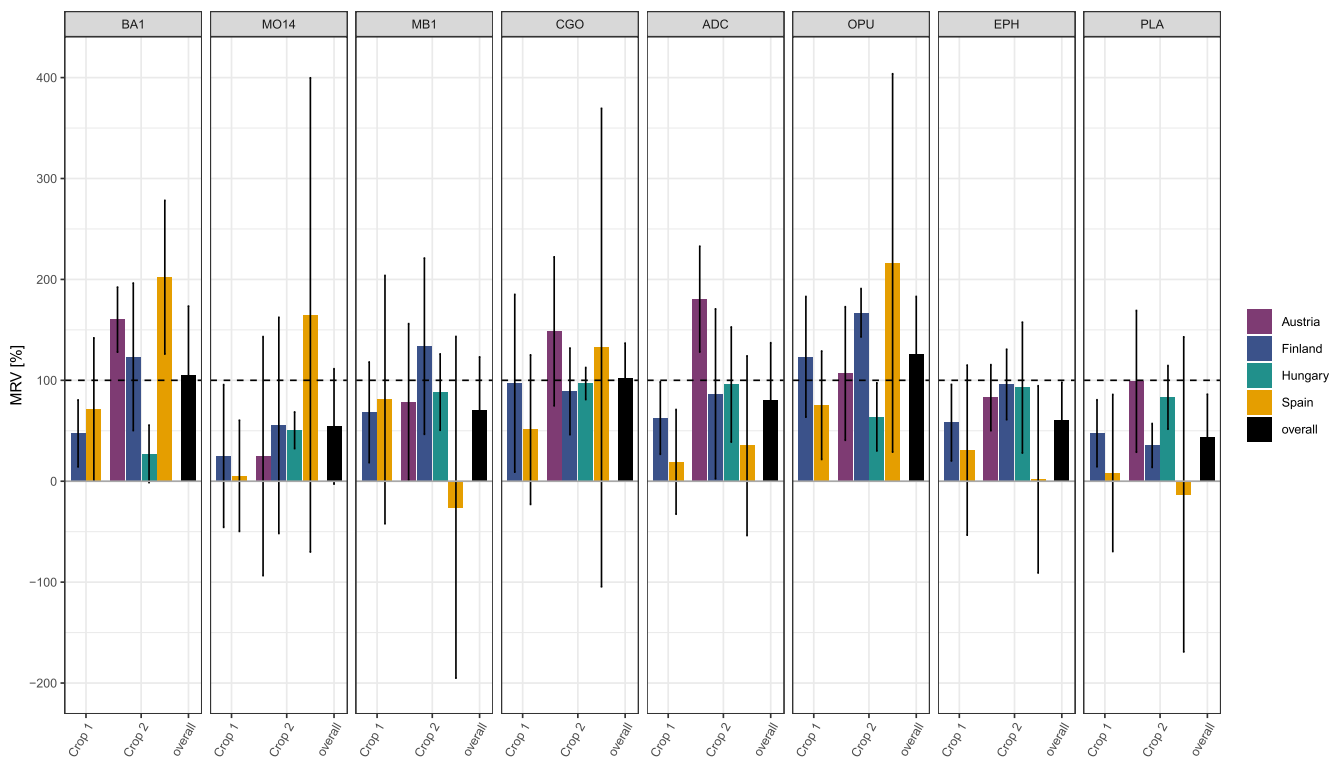


Fig. 5. Mineral replacement value (MRV) of the eight BBFs tested at each of the locations for the fertilised subplots. Data represents mean \pm standard deviation ($n = 4$). Overall mean was calculated from the mean values of the individual countries. Data for France and Hungary (first trial) were excluded due to non-responsive conditions. Data from the first year in Austria and Hungary (second trial) were excluded since grain yield was strongly affected by disease (Austria) or no grain could be harvested (Hungary).

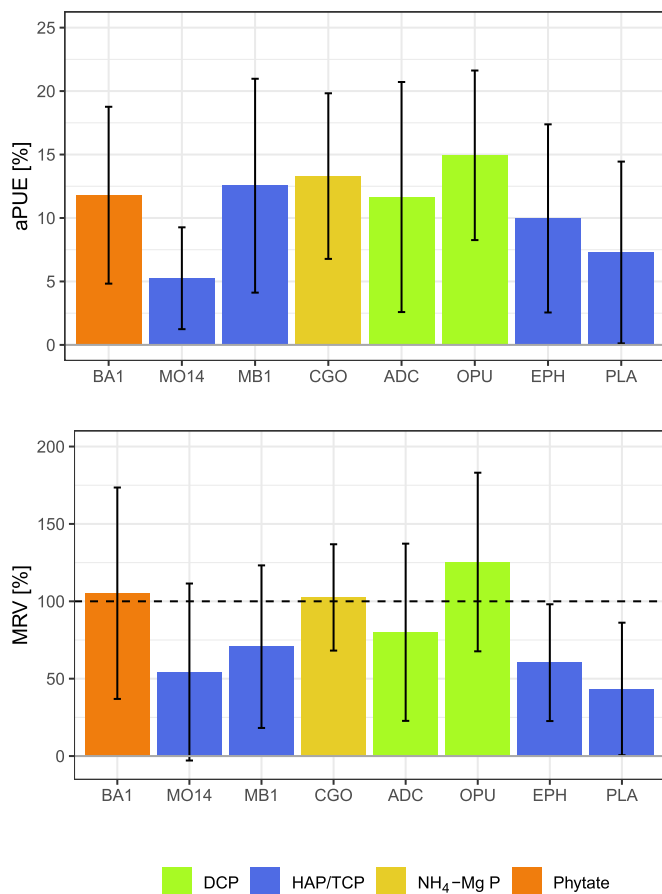


Fig. 6. Average apparent P use efficiency (aPUE) and mineral replacement values (MRV) of the eight BBFs tested in the field experiments with regard to dominant P species as determined by X-ray absorption near-edge structure (XANES) spectroscopy (Hernandez-Mora et al., 2024). Data correspond to the average values across sites and years for the fertilised subplots, only considering trials that showed a P fertilisation response (i.e. Finland, Spain; second crop in Austria and Hungary). DCP = dicalcium phosphate type species; HAP/TCP = hydroxyapatite/tricalcium phosphate; NH₄-Mg P = ammonium magnesium phosphate.

the site in Hungary (second trial) the response to P fertilisation could not be shown as drought hindered the occurrence of a clear yield response. In France, the measured Olsen P value was markedly above the estimated critical threshold value and no yield response could be observed (SI Figure 12). For two other sites (Hungary (first trial), Spain), the measured Olsen P values and the calculated threshold value were slightly below the estimated threshold. Those trials showed variable yield responses to increasing levels of P fertilisation. In Hungary (first trial), no yield response was observed (SI Figure 9), however, there was

Table 4

Relationship of Olsen P to the estimated critical soil threshold value as proposed by Recena et al. (2022).

Site	Olsen P	Estimated critical soil threshold value ^a	Ratio Olsen P / threshold value
	mg kg ⁻¹	mg kg ⁻¹	-
France	34.3	19.8	1.7
Austria	4.2	15.6	0.3
Finland	7.4	15.8	0.5
Hungary (1 st trial)	12.7	16.1	0.8
Hungary (2 nd trial)	16.5	26.4	0.6
Spain	8.1	8.6	0.9

^a Based on Recena et al. (2022), conservative model with $y = 49 - 0.016 \times \text{clay} - 3.81 \times \text{pH}_{\text{H}_2\text{O}}$. For clay content and pH see Table 3.

an increase in total P uptake (data not shown). In contrast, yield levels in Spain showed an increasing trend with rising additions of TSP (SI Figure 13).

4. Discussion

4.1. BBFs can replace inorganic fertilisers as P source for crops

We hypothesized that BBFs had the potential to replace conventional inorganic fertilisers as P source for crops achieving comparable yields and P uptake. Our results support this hypothesis as none of the tested BBFs resulted in a significant reduction in yield or total P uptake compared to the inorganic TSP reference treatment. Besides this overall trend in the field trials, there were some differences in the fertiliser performance between sites and years.

The availability of P from fertilisers depends on the contained P species and their solubility. Previous studies reported a good plant availability of struvites both in the season of application, but also with some delayed release in a subsequent crop (e.g. Vaneekhaute et al., 2016). Likewise, also in our set of field trials the struvite CGO was amongst the BBFs with the best performance (Fig. 6). The other fertilisers with an overall good performance had phytate (BA1) or dicalcium phosphate type species (OPU, ADC) as their main P forms. The good overall performance of the phytate-based BA1 is slightly in contrast to results from pot trials where BA1 had significantly lower replacement values than the TSP reference (Hernandez-Mora et al., 2024). Phytate needs to be hydrolysed before becoming plant available, thus, the longer duration of the field experiments might have contributed to the better performance of BA1 in the field as compared to the pot trials with rather short durations. Furthermore, the MRV of BA1 increased from the first to the second crop both in Finland and in Spain (Fig. 5), providing additional evidence that phytate had a rather slow release pattern. Higher enzymatic activities under field conditions due to additional release of phytase from plant roots and/or microorganisms could be another explanation for the different efficiency of BA1 in pot vs. field trials (Liu et al., 2022). Phytate availability to enzymatic hydrolysis is also regulated by sorption to iron oxides in soil, however, we do not have data on iron oxide content nor P sorption for the soils.

Dicalcium phosphate has a high solubility in NAC (Duboc et al., 2022) and is considered highly plant available. While having the same dominant P species, the two dicalcium type-based BBFs tested in our study differed strongly in their source material and processing technology (Table 2). OPU is classified as an organic fertiliser and is made from raw chicken manure. ADC is an inorganic mineral fertiliser based on calcined phosphate from sewage sludge ash that has been previously reported to have a good fertiliser effect (Hauck et al., 2021; Hermann and Schaaf, 2019; Kiani and Ylivainio, 2024). Both BBFs also performed well in the set of pot experiments conducted by Hernandez-Mora et al., (2024).

On average, hydroxyapatite/tricalcium phosphate-based fertilisers were the fertilisers with the lowest MRV in the current set of field trials (Fig. 6). Still, these fertilisers reached average MRVs of 55–70 %, except

for PLA which had an average MRV of only 43 % across the field trials. Considering the aPUE, MO14 and PLA did not show a considerable direct fertilising effect in the field experiments, with aPUE values of 5 and 7 %, respectively, which is in line with their poor NAC-solubility (Table 2). For EPH and MB1 the aPUE values were higher (10 and 13 %, respectively), as was their NAC solubility. These results align with a set of pot trials in which both EPH and MB1 had a good performance in two out of three trials, while MO14 and PLA performed badly in two out of three trials (Hernandez-Mora et al., 2024). As highlighted by Hernandez-Mora et al., (2024), the P availability of the BBFs is not only a function of feedstock, but also of processing. Both OPU and PLA consist of similar feedstock (poultry manure), but differ strongly in their P fertiliser effect. While OPU is produced from raw poultry litter without any thermal treatment, PLA was made from combusted turkey litter, indicating that treatment temperature has a major influence on the dominant P-species and resulting P availability (Bruun et al., 2017).

4.2. Pedoclimatic conditions, especially soil P status, affect agronomic performance of BBFs

We expected the fertilising efficiency of BBFs to be affected by an interaction between their chemical composition and pedoclimatic conditions, which ranged from Mediterranean climate in Spain to humid continental climate in Finland and included a range of soil types with clay contents from 2 % to 60 % and $\text{pH}_{\text{H}_2\text{O}}$ values from 5.1 to 8.0. Most soils were carbonate-free, except for the soil in Spain which contained substantial amounts of carbonates. Generally, solubility is high for many P species at neutral to slightly acidic pH, which was the case in most field trials sites of this study, except for the trial in Spain and the first trial in Hungary (Table 3). However, we did not find a consistent ranking of the BBFs neither between sites nor within the individual sites over the two years, partly contradicting this hypothesis.

Nonetheless, some differences in BBF performance between sites can be related to interactions between BBF characteristics and site conditions. In the second year of the Spanish field trial, MRVs of three hydroxyapatite/tricalcium phosphate-based fertilisers (MB1, EPH, PLA) were markedly lower than at the other sites, giving some indication that the high soil pH reduced solubilisation of these BBFs (Fig. 5). Apatite-based fertilisers have been reported to solubilize primarily under acidic soil conditions (Brod et al., 2015; Christiansen et al., 2020). Surprisingly, EPH was the only fertiliser with a significant residual effect in the Spanish field experiment despite the alkaline soil pH (Fig. 2, Fig. 3), which might be due to secondary P forms in this BBF that could not be unequivocally determined (Hernandez-Mora et al., 2024).

For an efficient P fertilisation strategy not only the properties of the fertiliser are important, but also the availability of P from the soil (Oberson et al., 2010). Different soil P tests are commonly used to assess available P (Blackwell et al., 2019; Vaneckhaute et al., 2016; Yli-Halla et al., 2016). Although we intended to conduct the trials on fields with low available P, the initial soil P status on some of the sites was quite high (Table 4). In fact, at two sites we could not observe any yield increase with increasing levels of TSP (France, Hungary first trial), hindering the objective assessment of fertiliser performance due to the high soil P availability. For the two sites with the most pronounced response to P fertilisation (Austria, Finland), the responsiveness could be readily predicted from comparing the Olsen P value of the soil and a threshold value calculated from the soil pH and the clay content (Table 4) (Recena et al., 2022). For the trial in France, the non-responsiveness was also in accordance with the prediction by the threshold value. For Hungary (first trial) and Spain, however, the calculated threshold values and the measured Olsen P values at the beginning of the experiment were roughly in the same range. For these trials, variable yield responses were observed, ranging from no yield response and a slight response in total P uptake (Hungary first trial) to responsive conditions both in terms of yield and total P uptake (Spain). Thus, for sites with Olsen P values close

to the calculated threshold, experimental assessment of the responsiveness may be required before conducting large field trials. Overall, high Olsen P levels in large parts of Europe make it advisable to evaluate soil P status of a given field both for planning of field experiments, but also in terms of P fertilisation needs and recommendations (Cadot et al., 2018; Recena et al., 2022).

4.3. Assessing the residual effect of BBFs requires prolonged experimental durations

In theory, most P-fertilisers do not exert their full effect in the first year and especially fertilisers based on P-species with a slow release pattern, or fertilisers with reduced P uptake in the first year due to other factors such as drought could be expected to have a residual effect in the following year. However, the results of the field experiments only partly confirm this hypothesis (Fig. 2, Fig. 3). In fact, at most trial sites, no significant residual effect of any of the fertilisers was observed. In the field trial in Finland, OPU was the BBF with the numerically highest yield and total P uptake both in the first year and in the residual year, although the effect was just not significant. The aPUE in the first year was less than 15 % (Fig. 4), indicating that the P uptake from the fertiliser was rather small ($< 5 \text{ kg P ha}^{-1}$) and, thus, more than 25 kg P ha^{-1} from the BBFs were left in the soil. In the case of the Spanish field trial, a residual effect (for EPH even significant) of the fertilisers on crop growth of a succeeding sunflower crop was observed. This finding can be related to the very poor P uptake in the first year due to drought. It indicates that under such dry conditions, the P from the BBFs remained in the soil and became or remained plant available in the following year. Likely, dissolution and subsequent sorption processes of P from the BBFs to soil particles were limited by the low availability of water in the soil, allowing plant P uptake by the second crop. Noteworthy, sunflowers are known to have a high P acquisition efficiency (Fernández et al., 2009). Since sunflower was only tested in Spain, the observed residual effect cannot be unequivocally distinguished from the effect of the chosen crop.

In a two-year study with 240 L containers investigating some of the BBFs tested within the field trials of the current study, Müller et al. (2024) found a residual effect of MO14, MB1 and OPU, exceeding the TSP reference treatment, but not a reference treatment fertilised with TSP and ammonium nitrate, in terms of dry matter yield in ryegrass grown after winter wheat. However, they used a nutrient poor soil-sand substrate with low P and low N availability. As especially MB1 and OPU contain also considerable amounts of N, the observed residual effect might at least partly relate to an additional N effect.

The absence of a clear residual effect in the field trials, especially for the BBFs with a poor performance in the first year, might relate to the fact that the application of BBFs was only done once at amounts according to common practice and that only one residual year was investigated, which might be too little time for the more recalcitrant P forms to become available. If they remain unavailable, it could be expected that P accumulates in soil over time, hence, build-up of legacy P would be the result (Bouwman et al., 2017; Gatiboni and Condron, 2021). Olsen P analysis after harvest of the first crops did not show any differences between treatments (data not shown), likely because under field conditions with their inherent high spatial variability it is often not possible to achieve measurable changes in soil extractable P from a single application of P fertilisers at standard rates. Lemming et al., (2019) showed that with repeated application of organic wastes, a substantial amount of residual P accumulated in soil that remained plant available for at least three years. In practice, also BBFs would presumably be applied repeatedly over the years, which might induce either an increasing residual effect over time or an accumulation of recalcitrant P in soil. Thus, the residual effect of BBFs after repeated application should be further investigated.

4.4. How to assess the fertilising efficiencies of novel BBFs – are field trials necessary?

In this study, we conducted field trials at five European locations during two years using the same eight BBFs. While it could be argued that field trials are unnecessary as the results can be obtained more easily and cost-effectively in pot trials, we are convinced that field trials remain indispensable for the evaluation of new BBFs.

Compared to a set of pot experiments in which the same BBFs were tested under controlled conditions (Hernandez-Mora et al., 2024), the overall performance of BBFs was similar. The pot trials allowed for the screening of a larger number of products and provided a mechanistic explanation of the behaviour of newly developed BBFs. However, pot studies usually do not assess the long-term fertiliser effect, and they do not allow for studying climatic effects on the fertiliser performance. Furthermore, pot studies have limited possibilities to study the effect of relevant agronomic practices such as the timing of BBF application, the choice of crops, the effect of crop rotations and application techniques including placement of the fertilisers. In contrast, our set of field experiments included different pedoclimatic conditions and were conducted following common agricultural practices, but had to be restrained to a limited number of fertilisers in order to be manageable. Especially for slow release P sources it has been shown that prolonged experimentation times are necessary to identify differences (Bogdan et al., 2021). The case of a phytate-based BBF (BA1), which performed better under field conditions than in the pot experiments, indicates that the longer duration and a potentially more active microbial community under field conditions facilitated the hydrolysis of phytates in soil, thus, pointing to the limitations of pot trials for the assessment of P fertiliser performance (Wollmann and Möller, 2018).

As it occurred with some trials in this study (Austria, Hungary, Spain), field experiments are prone to diseases and extreme weather conditions such as flooding or drought, hampering the objective assessment of fertiliser performance. While these factors seem unfortunate for a given experiment, they do reflect the reality and as such provide valuable information. For instance, drought in the first year of the Spanish trial might have allowed the BBFs to be preserved in the soil and to be available to crops in the next growing season (Fig. 2, Fig. 3).

Finally, only field experiments can prove whether or not a BBF is effective as P fertiliser under agronomically relevant conditions and with the machinery used in practice. We therefore strongly encourage that both pot experiments and field trials are used together to obtain a sound evaluation of BBFs. Furthermore, P-BBFs should be tested with a range of different crops as crops differ in their P acquisition patterns (Cadot et al., 2018; Richardson et al., 2009).

5. Conclusion

In the field trials under contrasting pedoclimatic conditions across Europe, none of the eight tested P-BBFs was significantly lower in fertilising efficiency than TSP, although biomass and P uptake after application of several BBFs also did not differ significantly from the control without P fertilisation. Averaged over sites and years, BBFs with struvite, dicalcium phosphate or phytate as main P-species performed best. Nonetheless, fertiliser performance varied between crops, years and sites, and no general pattern for the individual fertilisers or clear interactive effects with local pedoclimatic conditions could be found. We recommend that BBFs should be tested with additional crops that are sensitive to P fertilisation and on local farms so that regional recommendations for the use of BBFs can be based on locally validated first year and residual fertiliser replacement values. Ideally, if the data of these local experiments is shared openly, advice to farmers concerning the appropriate use of BBFs can be much improved.

In addition, it would be valuable to conduct investigations on fields

with even lower initial P status and over longer time spans with repeated fertiliser application in order to assess the long-term residual effect of the fertilisers. Longer experiments would also be recommended to investigate fertiliser-induced changes in soil biological and chemical properties such as pH and other micro- and macronutrient availability due to repeated application of BBFs.

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CRediT authorship contribution statement

Arkoun Mustapha: Methodology, Conceptualization. **Geyer Stefan:** Investigation. **Duboc Olivier:** Writing – review & editing, Investigation. **Santner Jakob:** Writing – review & editing, Methodology, Conceptualization. **Recena Ramiro:** Writing – review & editing, Investigation. **Tóth Zoltán:** Writing – review & editing, Methodology, Conceptualization. **Frick Hanna:** Writing – original draft, Visualization, Formal analysis. **Jauhiainen Lauri:** Investigation. **Bünemann Else K.:** Writing – original draft, Project administration, Methodology, Conceptualization. **Ylivainio Kari:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Hernandez-Mora Alicia:** Writing – review & editing, Investigation. **Eigner Herbert:** Investigation. **Delgado Antonio:** Writing – review & editing, Methodology, Conceptualization. **DOria Aurélien:** Writing – review & editing, Investigation.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.fcr.2025.109803](https://doi.org/10.1016/j.fcr.2025.109803).

Data availability

Data is deposited at Zenodo repository 10.5281/zenodo.14883600.

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