Journal of Plant Nutrition and Soil Science

WILEY-VCH

RESEARCH ARTICLE OPEN ACCESS

Enhancing the Fertilizer Value of Recycled Phosphorus for Horticulture Crops Through Acidification and Placement

Pietro Sica[1,2] | Dorette Müller-Stöver[1] | Jakob Magid[1]

[1]Department of Plant and Environmental Sciences, University of Copenhagen, Frederiksberg, Denmark | [2]Department of Food Sciences and Technology, College of Agriculture "Luiz de Queiroz", University of São Paulo, Piracicaba, Brazil

Correspondence: Jakob Magid (jma@plen.ku.dk)

Received: 20 December 2023 | **Revised:** 26 November 2024 | **Accepted:** 6 December 2024

Academic Editor: Thomas Eichert

Funding: This research was supported by the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie (grant 860127).

Keywords: digestate solid fraction | meat and bone meal | nutrient cycling | onion | pea

ABSTRACT

Background: Placement and acidification pretreatments are strategies to enhance the phosphorus (P) fertilizer value of biowastes. However, their impact on the commercial yield of horticultural crops and the effects on the contents of undesirable elements in the edible product are not well known.

Aims: The main objective of this study was to assess how the placement and acidification of biowastes affect commercial yield and nutritional quality of vegetables.

Methods: To investigate this, we selected two byproducts from agroindustries, meat and bone meal (MBM) and digestate solid fraction (DSF), and conducted a pot experiment with peas and onions growing in 10-L pots. Four treatments were assessed for each biowaste: untreated mixed (UM), untreated placed (UP), acidified mixed (AM), and acidified placed (AP).

Results: Acidification increased the water-soluble P of both byprodutcs to over 70% of the total P. For DSF, the AP treatment yielded over 100% more than UM, with a fertilizer value exceeding triple superphosphate. However, for MBM, no significant differences were found among UM, AM, and AP treatments, with UP yielding even less than the negative control, indicating a toxicity effect, probably of ammonium that reduced plant growth. Although acidification may have increased the solubility of undesirable elements, it was not reflected in plant composition, as higher P solubility contributed to increased commercial yields, diluting undesirable element content.

Conclusions: Therefore, the placement of acidified DSF shows promise in improving fertilizer value, with no adverse effects on the content of undesirable elements in onion bulbs and pea grains.

1 | Introduction

Consumer habits are shifting in favor of more environmentally friendly and sustainable food production systems (Reisch, Eberle, and Lorek 2013; Vermeir et al. 2020). In this context, increasing the efficiency of recycled phosphorus resources in agriculture is an alternative to reduce the dependence on nonrenewable P fertilizers, thereby producing food with reduced inputs in line with circular farming practices (Recena et al. 2022). However, recycled phosphorus resources such as meat and bone meal (MBM) and the solid fraction of digestate, a residue from biogas production, often have a lower fertilizer value compared to mineral fertilizers (Möller et al. 2018). Therefore, treatments and practices that can enhance the fertilizer value of these materials

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merit research. This will make these resources more attractive to farmers as a replacement for mineral fertilizers.

As early as in the late 1940s and 1950s, several studies by Cooke (1949a, 1949b, 1951, 1954) showed that placing mineral P fertilizers increased phosphorus uptake and plant growth in row horticultural crops compared to broadcast application. The placement of mineral fertilizer reduces the contact area with the soil and thereby the sorption of phosphorus (Meyer et al. 2023), creating a phosphate-rich zone that stimulates root growth and can increase crop growth at early growth stages (van der Bom et al. 2023). Recent studies have shown, however, that the placement of biowastes did not yield promising results. Lemming et al. (2016) found that the placement of sewage sludge increased root proliferation in the placement zone but did not enhance plant growth or P uptake when compared to treatments where the sludge had been mixed into the soil. Biowastes have relatively low soluble P contents, which are sufficient to promote root growth in the placement zone, but not enough to provide the total amount of P required, thus limiting plant growth over longer periods (i.e., weeks or months).

MBM is a residue from slaughterhouses, consisting mainly of bones, blood, and dried and milled meat (Möller 2015). It has relatively high nitrogen (≈10%) and phosphorus (≈2%–4%) contents; however, the average P use efficiency is low compared to mineral fertilizers, ranging from 17% to 67% (Brod et al. 2015a; Brod et al. 2015b; Christiansen et al. 2020). Damaceno et al. (2019) found that the acidification of MBM increased these values from 17% to 74%, indicating that this treatment could be a promising approach to increase the P fertilizer value of this biowaste.

The process of separating solid and liquid components in animal slurry/manure and digestate is a simple technology that enables the recovery of most of the nitrogen and soluble organic matter in the liquid fraction and the phosphorus in the solid fraction. This allows for more efficient management of digestate nutrients (Chuda and Ziemiński 2021; Tambone et al. 2017). In the digestate solid fraction (DSF), 15% of the total phosphorus is soluble in water (Sica et al. 2023) and Regueiro et al. (2020) found that acidifying this material increased phosphorus solubility to more than 70% of the total phosphorus, resulting in increased phosphorus uptake compared to unacidified material.

On the basis of this, Sica et al. (2023) tested different pretreatments to increase the P solubility of these biowastes. They found that acidification (H_2SO_4) of the solid fraction of biogas digestate and MBM significantly increased the fraction of water-soluble P of these materials as well as in the soil surrounding the placement zone. In another study, Sica et al. (2023) found that the placement of acidified DSF and MBM significantly increased the P uptake of wheat, compared to the respective untreated materials.

However, depending on the target pH, acidification may solubilize elements other than P, such as calcium, magnesium, and potassium. Acidification can also solubilize heavy metals, such as cadmium, or metals that become phytotoxic with increased plant availability in the soil, such as aluminum and iron, and affect their contents in the plant shoots and its edible parts (Keskinen et al. 2023).

On the basis of this background, we hypothesized that:

1. The placement of acidified DSF and MBM will enhance phosphorus uptake by onions and peas, leading to increased commercial yields for both crops.
2. Acidification will not only solubilize phosphorus but also undesirable elements (i.e., Cd, Cu, and Al), potentially increasing their dry matter contents in the edible parts of onions and peas.

To test these hypotheses, the DSF and MBM (untreated or acidified, both treatments either mixed or placed in the soil) were assessed as phosphorus fertilizers in a setup where onions and peas were grown to maturity and their edible parts harvested, with the objective to evaluate the effect of the different P fertilizers on the commercial yield of the crops, as well as on the nutrient composition of their bulbs and grains, respectively. Both crops were selected because of their high responsiveness to phosphorus. Peas, as legumes, are known to have high phosphorus requirements, particularly in the early stages of nodule formation for nitrogen fixation (Sulieman and Tran 2015; Powers et al. 2020). On the other hand, onions are row horticultural crops with shallow root systems and limited soil exploration, making them highly responsive to the placement of phosphorus (Brewster 2009; Goswami and Kalidas-Singh 2023).

2 | Materials and Methods

2.1 | Soil

The soil used in the present study was collected in 2022 from the negative control treatment (unfertilized plot since 2003) of the long-term field trial known as "CRUCIAL," located 20 km west of Copenhagen (geographical coordinates 55°40′N, 12°16′E). The soil is categorized as a sandy loam and is a Luvisol according to the FAO classification. Its average texture is 26.2% coarse sand, 43.6% fine sand, 14.3% silt, and 12.6% clay.

The collected soil had a pH of 6.6 (in water) and a total phosphorus content of 0.51 mg g^{-1} soil. Notably, 1.6% of this phosphorus content (equivalent to 8 mg kg^{-1}) was extractable using an anion exchange resin. A comprehensive overview of the soil's chemical composition is given in Table 1. Additional information on the CRUCIAL trial and more specific characteristics of the soil from the unfertilized plots can be found in Gómez-Muñoz et al. (2018) and Lemming et al. (2019).

2.2 | Fertilizers

In this study, five fertilizers were assessed. Triple superphosphate (TSP) served as the reference mineral fertilizer, characterized by a total phosphorus content of 20.8%, of which 73% was found to be extractable using an anion exchange resin.

Two other materials, the DSF and MBM, were used in their untreated and acidified states (four fertilizers). The DSF was sourced from the Maabjerg Energy Center in Holstebro, Denmark, where a mixture of approximately 70% cattle manure, 20%

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TABLE 1 | Composition of the fertilizers and soil used in this study.

		Soil	Digestate solid fraction		Meat and bone meal	
			Untreated	Acidified	Untreated	Acidified
C[a]	(g kg^{-1})	13	340	271	428	401
N[a]		16	26.5	20.6	98.4	90.3
P[b]		0.51	34	28.7	34.2	28.6
S[b]		0.21	9.1	112	4.9	41.7
Al[b]		16.7	1.06	0.97	0.29	0.48
Ca[b]		2.79	50.4	36.2	60.6	50.6
Fe[b]		6.95	6.66	4.73	1.47	1.33
K[b]		10.1	12.6	7.84	7.11	6.09
Mg[b]		0.95	22.0	13.9	1.55	1.28
Na[b]		1.84	3.05	1.44	5.73	4.99
Cd[b]	(mg kg^{-1})	0.52	0.36	0.32	0.27	0.11
Cr[b]		16.7	11.9	9.4	3.9	3.9
Cu[b]		5.92	102	87	18.7	19.1
Zn[b]		36.4	472	404	127	140
pH		6.6	9.1	3.2	5.8	3.9
Resin P[c]	(% total P)	1.6	14	59	2.3	83

[a]Carbon and nitrogen contents were determined by an elemental analyzer on dried samples (Vario macro cube, Elementar Analysensysteme GmbH, Germany).
[b]Contents were determined by ICP-OES (Agilent 5100) after microwave-assisted digestion with HNO_3, H_2O_2, and HF.
[c]Determined by shaking two anion exchange resin strips (1 cm × 5 cm) with equivalent to 2 g of dry soil in 20 mL of water for 1 h. More information regarding this procedure can be found in Siegenthaler et al. (2020).
Abbreviations: DA = digestate solid fraction acidified = DU = digestate solid fraction untreated = MA: meat and bone meal acidified; MU = meat and bone meal untreated.

pig slurry, 8%–9% chicken manure, and up to 2% food waste is used as reactor substrate. Detailed insights into the composition of the DSF can be found in the work of Liu, de Neergaard, and Jensen (2019). The MBM was collected from the Daka SecAnim plant in Hedensted, Denmark. This material consists mainly of residues from slaughterhouses, including bones, meat, and blood.

Both the MBM and the DSF were acidified according to the established protocol previously described by Sica et al. (2023). The amount of concentrated sulfuric acid applied was 50 mL kg^{-1} of material, on the basis of the results of Sica et al. (2023), with the aim of ensuring that at least 70% of the total phosphorus content in each material would become soluble in water.

Briefly, for MBM acidification, 350 g of dried MBM were placed in a 1-L container. Subsequently, 1 M sulfuric acid was applied at a rate of 1 mL per 2 g of material dry weight. This acid was carefully mixed with the MBM to ensure uniform wetting. Following this, the acidified material was placed in an oven and kept at 65°C for 48 h. The dried and acidified material was crushed and sieved to particles smaller than 2 mm using a mortar and pestle to make it suitable for use as a fertilizer.

The process for acidifying the DSF was essentially the same, with one notable adjustment. Due to the lower density of the DSF material, a larger volume of solution was applied. Specifically, 1 mL of 1 M sulfuric acid plus 1 mL of Milli-Q water were added per 2 g of material dry weight.

2.3 | Experimental Setup

An overview of the experimental setup and the plant growth conditions is presented in Figure 1. The plant growth experiment was conducted in pots with a volume of 10 L, each carefully filled to achieve a bulk density of 1.2 g cm^{-3}.

The filling process involved four distinct layers, each composed of a mixture of 3 kg of soil and quartz sand with a grain size of 0.4–0.8 mm, combined in a 3:1 ratio (2.25 kg of soil and 0.75 kg of sand, measured in dry weight). Notably, the three lower layers remained unfertilized. This layered arrangement ensured proper compaction of the soil at different depths, which facilitate the filling process of the pot, while limiting fertilization exclusively to the top layer.

The top layer, however, was fertilized with nutrient solutions providing all essential plant nutrients except phosphorus. This nutrient supplementation was applied (in mg) as follows: N = 450; K = 450; Ca = 120; Mg = 120; S = 60; Cu = 4.5; Zn = 3.6; Mo = 0.3; Fe = 9; B = 0.9; and Mn = 9. After fertilization, the soil was carefully homogenized to ensure uniform nutrient distribution. As each pot contained only one plant, nutrient application rates were calculated on the basis of the expected total dry matter per plant by the end of the experiment. To avoid limiting plant growth by nutrients other than phosphorus, all nutrients were applied at rates at least twice the expected plant requirements. In previous studies, similar nutrient application rates were used for onions,

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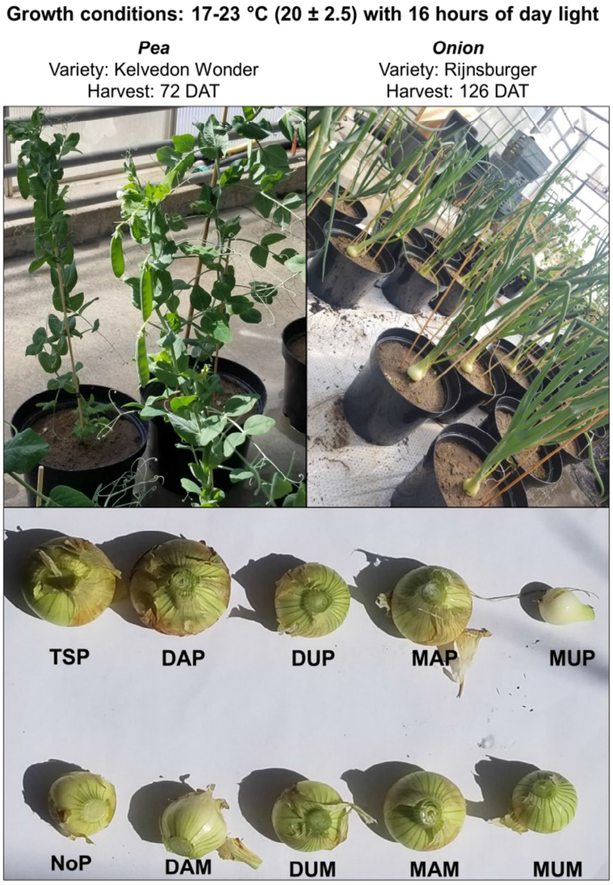

FIGURE 1 | Overview of the experimental design and plant growth conditions in this study. Images in the top left and right represent peas (60 days after transplanting, DAT) and onions (105 DAT), respectively. The picture at the bottom represents the onion bulbs of all treatments assessed in this study just after harvest (126 DAT). 1st letter = D: digestate solid fraction; M: meat and bone meal; 2nd letter = A: acidified; U: untreated; 3rd letter = M: mixed; P: placed. DUM, DSF untreated mixed; TSP, triple superphosphate.

peas, and other crops, and no nutrient deficiencies were observed in the plants (Gómez-Muñoz et al. 2018; Sica et al. 2023,Sica, Kopp et al. 2024; Sica, Müller-Stöver et al. 2024; Sica and Magid 2024).

The negative control (referred to as "N") was soil supplemented with all essential nutrients except phosphorus. Furthermore, a reference control was established, using TSP in powder form. The TSP was applied at a rate of 180 mg of total P per pot, equivalent to 60 mg of P per kilogram of soil in the top layer. The TSP was homogeneously mixed into the top layer of the soil to ensure an even distribution. As the top layer of the pot was 5 cm deep, the total phosphorus applied in this layer was 36 kg ha. This application rate is comparable to the approx. 30 kg of total phosphorus per hectare, which is the threshold value set by the Danish Ministry of Food and the Environment (Miljøstyrelsen 2018).

Both the MBM and the DSF were applied in identical treatments, which included the following: (1) untreated mixed (UM), (2) untreated placed (UP), (3) acidified mixed (AM), and (4) acidified placed (AP). The fertilizers were applied at a rate of 180 mg of total phosphorus per pot, corresponding to 60 g of phosphorus per kilogram of soil in the top layer.

For the "mixed" treatments (M), the fertilizers were uniformly mixed with the soil of the top layer before being added to the pots. Conversely, for the "placed" treatments (P), the soil was first added to the pots, and then soil from the center of the pot was removed to a depth of 10 cm using a tube with a 5-cm diameter. In this hole, the fertilizer was applied and subsequently packed with the soil that had been removed.

After the application of the fertilizers and the proper packing of soil in the pots, an appropriate volume of water was added to achieve a soil moisture content of 60% of the soil water holding capacity (29 g of water per 100 g of dry soil). Subsequently, the tops of the pots were sealed with plastic bags, and this moisture content was maintained for 1 week in order to stimulate and revitalize the soil microbial activity, as described by Oehl et al. (2004).

2.4 | Plant Growth Conditions

Onion (*Allium cepa*, cv. Rijnsburger) and pea (*Pisum sativum*, cv. Kelvedon Wonder) were grown under uniform conditions, with the fertilizer treatments as described above. Consequently, each crop was subjected to a total of 10 different treatments, as illustrated in Figure 1, with each treatment being replicated 4 times, resulting in a total of 40 pots per crop.

Onion and pea seeds were pre-germinated by placing them in moist paper sheets for a 5-day period, at a controlled temperature of 20°C in a dark environment. Seedlings for transplantation were carefully selected to ensure uniform height. In each pot, two seedlings were initially placed, and after 5 days, one seedling was removed.

In the greenhouse, the temperature was monitored hourly and had a daily average of 20°C ± 2.5°C. To maintain a consistent photoperiod conducive to plant growth, a 16-h day length was established. To achieve this, LED lights were placed above the pots and programmed to activate automatically to supplement light and complete the day cycle during dark hours or cloudy days. The experiments were carried out from January to May 2023 in Copenhagen, Denmark. Therefore, light was specially supplemented at the beginning of the experiment.

The pots were manually watered with the same amount of water every 3 days for the first 45 days. After that, the pots were watered every 2 days. At each watering, weeds were removed and the pots were randomly rotated. Bamboo sticks were used to direct and support the growth of the above ground biomass (Figure 1).

2.5 | Harvest

The crops had different growth cycle lengths and were therefore harvested at different times. Pea plants predominantly entered the flowering stage at 40–42 days after transplanting (DAT), with pod development commencing at 45–50 DAT. Pea pods

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were harvested at 76 DAT, when both the plant shoots and pods had begun to dry. The fully developed pods were manually separated from the plant, opened, and the grains were removed. For each plant, the number of pods and the number of grains were counted, and the average number of grains per pod was also determined. The pea grains were weighed, and the fresh weight was determined. The shoots were cut close to the soil surface. Grains and shoots were dried in an oven at 60°C for 48 h, and the dry matter was determined.

Onion bulbs were harvested at 126 DAT, when the treatment with the smallest bulbs had reached a minimum size for further analyses (MUP, in Figure 1). The shoots were cut at the top of the onion bulbs, and roots were removed. For each plant, the fresh weight and diameter of the bulbs were determined. Bulbs were cut into four pieces, and bulbs and shoots were dried in an oven at 60°C for 48 h to determine their dry matter.

2.6 | Plant Analyses

To avoid contamination by metals, all cutting during the harvest was done with a ceramic blade knife made of zirconium oxide (Kyocera). The plant material (shoots, bulbs, and grains) was milled to a fine powder with zirconium balls. The samples (100 mg) were microwave-digested with 2.5 mL of 70% HNO_3 and 1 mL of 15% H_2O_2. After that, Milli-Q water was added to bring the volume to 50 mL. The elemental composition of the plant material was then determined by inductively coupled plasma-mass spectrometry (ICP-MS, Agilent 7900, California, USA). The nitrogen content was determined using an Elemental Analyzer (Vario macro cube, Elementar Analysensysteme GmbH, Germany).

2.7 | Calculations

The nutrient uptake (in mg per plant) was calculated as the nutrient content (in mg g^{-1} of dry matter) multiplied by the dry matter (in g per plant).

The mineral fertilizer equivalent (MFE) was calculated according to the following equation:

$$\text{MFE of treatment (\%)} = 100 \times \frac{(\text{Treatment} - N)}{(\text{TSP} - N)}, \qquad (1)$$

where Treatment − N is the difference between the results for that treatment and the negative control (N), and TSP − N is the difference between the results for TSP (the mineral fertilizer) and the negative control.

The MFE was calculated in terms of total P uptake (shoots + bulbs/grains) and commercial yield (in dry matter of bulbs or grains). Results around 100% indicate that the treatment had a performance similar to the mineral fertilizer, whereas results above 100% indicate a better performance of the treatment. Negative values indicate that the treatment performed worse than the negative control.

2.8 | Statistics

This study was not designed to statistically compare different crops or different materials (i.e., pea vs. onion or DSF vs. MBM). Thus, all the statistical analyses were performed for each material in each crop, using IBM SPSS Statistics 27.0. The homogeneity of variance of the data was verified using Levene's test, and the Kolmogrov–Smirnov test was used to verify that the data followed a normal distribution. For each material, a two-way ANOVA was performed to assess whether there were significant effects (p value < 0.05) of acidification (untreated vs. acidified), application methods (mixed vs. placed), and their interactions on the analyzed parameters. In case of a significant interaction, the Tukey HSD test was performed (<0.05) for multiple comparisons of means. These differences are indicated in the figures and tables. Principal component analysis (PCA) analysis was performed on the yield (DM) and the elemental contents in the commercial products (grains and bulbs) using SigmaPlot 15.0. To normalize the data, the respective mean was subtracted from each data point and then divided by the standard deviation.

3 | Results

3.1 | Yield

The DSF treatments did not have a significant effect on shoot dry matter for any of the crops. For bulbs and grains, acidified DSF placed (DAP) resulted in the significantly highest yield (dry matter). For pea, there was also a significant overall positive effect of placement, such that the DSF untreated mixed (DUM) had the lowest grain DM. In terms of total aboveground biomass, the DAP treatment was significantly higher than DUM for onions and significantly the highest for peas (Figure 2). In terms of grain and bulb fresh weight, there was a significant interaction between acidification and application methods, with DAP resulting in the highest yields for both onion and pea (Table S1) and in the largest diameters for onions (Table S2). For pea, the localized application of DSF had a significant effect increasing the number of pods per plant, grains per plant, and grains per pods (Table S2).

For MBM, in both crops, the dry matter yield of bulbs and grains as well as the dry matter of the shoots and the total aboveground dry matter showed significantly lower values in the untreated placement (MUP) treatment compared to the other treatments. No significant difference was observed between the other treatments (MAP vs. MAM vs. MUM) (Figure 2). For onion, MUP also resulted in significantly smaller bulbs (Table S2).

3.2 | Macronutrient Uptake

For onions that received DSF fertilization, both the P uptake by bulbs and the total P uptake were significantly higher with DAP compared to the other treatments (Figure 3). In the case of peas, no interaction was observed affecting the P uptake by shoots and the total P uptake. However, with respect to grains, DAM and DAP exhibited significantly higher uptake compared to DUM and DUP (Figure 3). For onion, acidification and placement significantly increased K uptake in bulbs, whereas placement also significantly increased S uptake in bulbs (Table 2). For peas,

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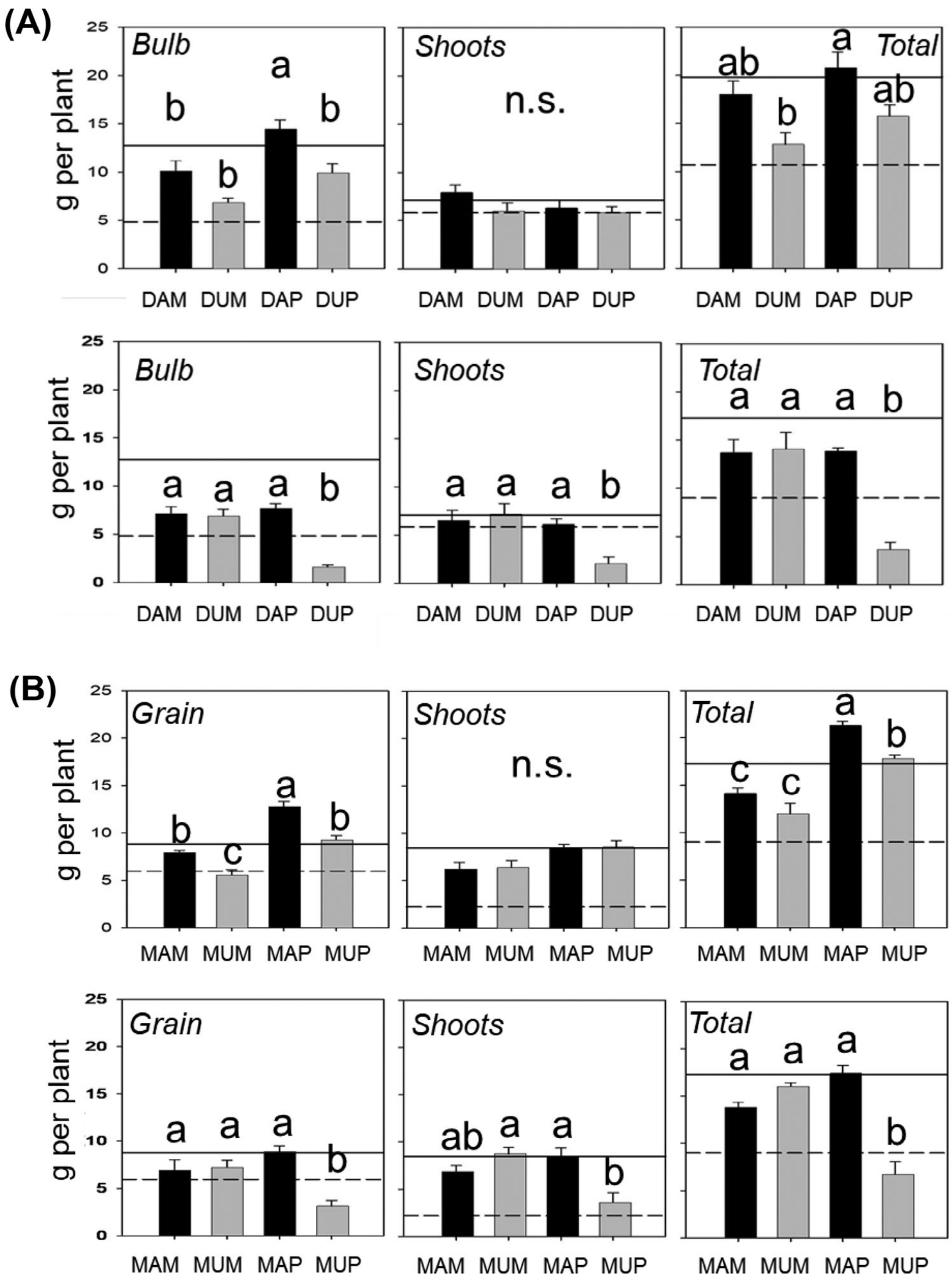

FIGURE 2 | Onion bulbs, shoots, and total (bulbs + shoots) dry matter (A) and pea grains, shoots, and total (grains + shoots) dry matter (B). The solid line represents the average values for triple superphosphate (TSP) and the dashed line represents the average values for the negative control (N). "n.s.": no significant interaction between treatment (acidification) and application methods. Different letters indicate a significant difference between treatments (Tukey HSD < 0.05) for parameters with a significant interaction between treatment (acidification) and application methods. 1st letter = D: digestate solid fraction; M: meat and bone meal; 2nd letter = A: acidified; U: untreated; 3rd letter = M: mixed; P: placed. DUM, DSF untreated mixed.

DSF acidification significantly increased N, K, S, and Ca uptake in grains, whereas placement increased K, S, and Ca uptake in grains, and S and Ca uptake in shoots (Table 3). Conversely, when onions and peas were fertilized with MBM, the total P uptake for MUP was significantly lower compared to the other treatments. The latter also applied to onion bulbs (Figure 3). This trend of lower nutrient uptake with MUP was also observed for N, K, S, and Ca in shoots, grains, and bulbs (Table 3).

The total MFE for yield DM and total P uptake for both crops was higher than 100% for DAP, indicating that it had a better effect than TSP (Table S1). In the case of MBM, the MUP had negative MFEs for onion yield and total P uptake, and for pea total P uptake, indicating that the treatments were less effective than the unfertilized control for these parameters (Table S1).

3.3 | Element Content in Dry Matter

For onions fertilized with DSF, the contents in dry matter of the macronutrients N, P, K, S, and Ca in shoots and bulbs (Table S3) and the contents in dry matter of metals Al, Fe, Co, Cu, Zn, and Cd in bulbs were not significantly affected by acidification,

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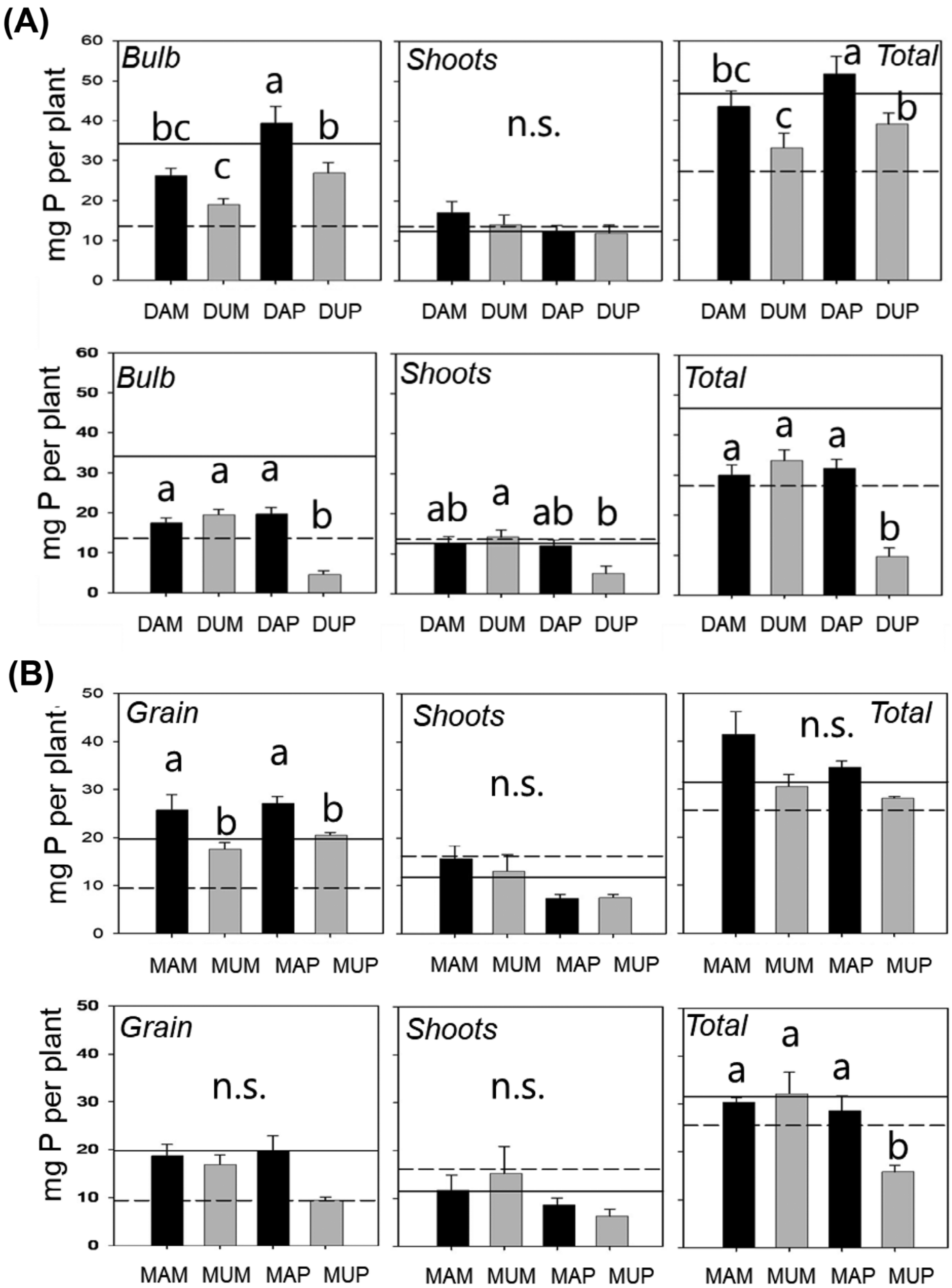

FIGURE 3 | Total P uptake by onion bulbs, shoots, and total (bulbs + shoots) (A) and pea grains, shoots, and total (grains + shoots) (B). The solid line represents the average values for triple superphosphate (TSP) and the dashed line represents the average values for the negative control (N). "n.s.": no significant interaction between treatment (acidification) and application methods. Different letters indicate a significant difference between treatments (Tukey HSD < 0.05) for parameters with a significant interaction between treatment (acidification) and application methods. 1st letter = D: digestate solid fraction; M: meat and bone meal; 2nd letter = A: acidified; U: untreated; 3rd letter = M: mixed; P: placed. DUM, DSF untreated mixed.

application method, or the interaction between these factors (Table 4). The PCA indicated that for DSF, the yield of onion was not closely associated to any of the element contents in dry matter, and P had a negative relationship with yield (PC1: 45.25%, and PC2: 23.45%; Figure S1), indicating a dilution effect. Phosphorus and calcium (Table S3), as well as copper contents (Table 4) in bulb dry matter, had a significant and negative Pearson correlation with yield DM.

For onions fertilized with MBM, N, P, and K contents in shoot and bulb dry matter were significantly lower in the acidified treatments (except for P in bulbs) and had a significant and negative correlation with yield (Table S3). The PCA (PC1: 48.64%; PC2: 22.65%) indicated that yield was not associated with the other parameters (Figure S1). For the metals, Al, Fe, and Co were significantly lower in the mixed treatments. These three elements plus copper had a significant and negative correlation with yield (Table 4).

For peas fertilized with DSF, N, P, and K contents in dry matter of shoots and grains were negatively correlated with yield DM (Table S4). These parameters were also significantly

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TABLE 2 | Nitrogen (N), potassium (K), sulfur (S), and calcium (Ca) uptake by onion bulbs and shoots, and pea grains and shoots for the different fertilization treatments used in this study.

Onion								
	N		**K**		**S**		**Ca**	
	(mg plant^{-1})							
	Bulbs	**Shoots**	**Bulbs**	**Shoots**	**Bulbs**	**Shoots**	**Bulbs**	**Shoots**
N	54 ± 5.4	118 ± 14	53.7 ± 0.8	164 ± 17	25.0 ± 1	37 ± 2	138 ± 2	6.9 ± 13
TSP	161 ± 9	144 ± 24	142.3 ± 2.2	194 ± 5	65.4 ± 2	132 ± 7	167 ± 8	26.6 ± 13
Digestate solid fraction								
DAM	120 ± 12	170 ± 16	102 ± 8 b	199 ± 31	47 ± 3 ab	122 ± 5	153 ± 10	20.9 ± 13
DUM	88.7 ± 4.8	139 ± 23	73.5 ± 5 c	167 ± 24	34 ± 5 b	87 ± 5	138 ± 2	15.4 ± 12
DAP	182 ± 37	128 ± 20	167 ± 9 a	167 ± 22	79 ± 5 a	178 ± 5	148 ± 8	34.4 ± 30
DUP	119 ± 9.9	122 ± 11	112 ± 8 b	152 ± 20	53 ± 3 ab	140 ± 3	156 ± 10	26.1 ± 13
p value								
Acidification	—	—	***	—	—	—	—	—
Application	—	—	***	—	*	—	—	—
Interaction	—	—	—	—	—	—	—	—
Meat and bone meal								
MAM	93 ± 10 a	152 ± 22	72.9 ± 7 a	174 ± 42 a	41.2 ± 5 a	97 ± 8 b	137 ± 4 a	18.3 ± 3 a
MUM	104 ± 16 a	178 ± 26	73.0 ± 7 a	220 ± 28 a	40.1 ± 4 a	100 ± 9 b	169 ± 6 a	21.0 ± 3 a
MAP	100 ± 12 a	151 ± 24	77.5 ± 9 a	161 ± 12 a	39.4 ± 5 a	129 ± 1 a	162 ± 4 a	24.4 ± 1 a
MUP	26.2 ± 3 b	63.3 ± 17	21.6 ± 2 b	77 ± 21 b	8.1 ± 1 b	49 ± 4 c	81 ± 1 b	9.5 ± 1 b
p value								
Acidification	*	—	**	—	**	—	***	—
Application	*	—	*	*	**	*	**	*
Interaction	**	—	*	*	*	*	*	—

Note: First letter = D: digestate solid fraction; M: meat and bone meal; Second letter = A: acidified; U: untreated; Third letter = M: mixed; P: placed. Two-way ANOVA, *p* value: >0.05; *≤0.05; **<0.01; ***<0.001; the mean is followed by the ± standard errors. Different letters indicate a significant difference between treatments (Tukey HSD < 0.05).
Abbreviations: DUM = DSF untreated mixed; N = no phosphorus applied; TSP = triple superphosphate.

lower for the placed fertilizers compared to the mixed (except for K in grains). The PCA (PC1: 65.31%; PC2: 16.72%) indicated that yield was closely related to calcium, cobalt, and cadmium contents in grain dry matter (Figure S1). The Ca content in grains was positively correlated with yield (Table S4); however, Co and Cd had no significant correlation with yield (Table 5). Copper was negatively and significantly correlated with yield (Table 5).

On the other hand, for peas fertilized with MBM, the treatments had no significant effect on N, P, K, S, and Ca contents in grain and shoot dry matter. N and P contents in shoots and grains (Table S4), as well as Cu, Co, and Zn contents in grain dry matter (Table 5), were negatively correlated with yield. The PCA (PC1: 52.25; PC2: 32.32) partially confirmed this, as Cu, P, and N contents in grains were associated, whereas yield was closer associated with Ca content in grain dry matter (Figure S1). Ca contents in grain and shoot dry matters were positively correlated with yield (Table S4).

4 | Discussion

The objective of this study was to evaluate how the acidification and placement of the DSF and MBM affected the commercial yield of onions and peas, as well as the nutrient composition of their bulbs and grains, respectively. Therefore, we did not intend to compare materials (MBM vs. DSF) but rather to examine how the acidification and placement of each material affected the assessed parameters for both crops compared to their untreated and mixed treatments.

4.1 | Fertilizer Composition and Effects of Treatments on P Solubility

In the process of separating the digestate into solid and liquid fractions, most of the nitrogen and soluble organic matter is in the liquid part, whereas phosphorus and more stable forms of organic matter are retained in the solid portion (Tambone et al.

TABLE 3 | Nitrogen (N), potassium (K), sulfur (S), and calcium (Ca) uptake by onion bulbs and shoots, and pea grains and shoots for the different fertilization treatments used in this study.

Pea	N		K		S		Ca	
	(mg plant^{-1})							
	Grain	Shoots	Grain	Shoots	Grain	Shoots	Grain	Shoots
N	74.6 ± 9	168 ± 21	37 ± 6	138 ± 12	6.9 ± 1	32.6 ± 11	4.9 ± 4	261 ± 90
TSP	177 ± 7	170 ± 40	132 ± 2	167 ± 20	26.6 ± 0.5	50 ± 5	53.1 ± 0.5	629 ± 27
Digestate solid fraction								
DAM	209 ± 25a	191 ± 37	122 ± 5ab	153 ± 18	20.9 ± 7ab	36.6 ± 7b	37.1 ± 6b	456 ± 82c
DUM	153 ± 23b	158 ± 18	87.0 ± 9b	138 ± 14	15.4 ± 5b	32.9 ± 5b	19.0 ± 3c	439 ± 98c
DAP	225 ± 14a	125 ± 6	178 ± 6a	148 ± 7	34.4 ± 2a	51.6 ± 2a	63.6 ± 3a	916 ± 18a
DUP	159 ± 9b	133 ± 17	140 ± 4a	156 ± 13	26.1 ± 3a	47.8 ± 3a	47.0 ± 8ab	788 ± 30b
p value								
Acidification	*	—	***	—	***	—	**	—
Application	—	—	***	—	***	*	***	***
Interaction	—	—	—	—	—	—	—	—
Meat and bone meal								
MAM	157 ± 13a	160 ± 20	97 ± 12ab	137 ± 1ab	18.3 ± 7b	38.3 ± 7	27.9 ± 7ab	542 ± 99b
MUM	147 ± 18a	219 ± 33	100 ± 9ab	169 ± 15a	21.0 ± 5b	42.3 ± 5	31.7 ± 4ab	675 ± 82b
MAP	169 ± 15a	163 ± 27	129 ± 9a	162 ± 18ab	24.4 ± 5a	45.2 ± 5	40.6 ± 4a	838 ± 65a
MUP	87.6 ± 3b	87.2 ± 13	49 ± 4b	81.0 ± 19b	9.5 ± 5c	20.0 ± 5	10.2 ± 2b	235 ± 62c
p value								
Acidification	*	—	*	—	*	—	*	*
Application	—	—	—	—	—	—	—	—
Interaction	—	—	**	**	**	—	*	**

Note: First letter = D: digestate solid fraction; M: meat and bone meal; Second letter = A: acidified; U: untreated; Third letter = M: mixed; P: placed. Two-way ANOVA, p value: >0.05; *≤0.05; **<0.01; ***<0.001; the mean is followed by the ± standard errors. Different letters indicate a significant difference between treatments (Tukey HSD < 0.05).

Abbreviations: DUM = DSF untreated mixed; N = no phosphorus applied; TSP = triple superphosphate.

2017; Chuda and Ziemiński 2021). The phosphorus components mainly consist of calcium- and magnesium-bound phosphorus and struvite that precipitates in the anaerobic digestion reactor (Möller and Müller 2012). These P species can be dissolved at lower pH, as demonstrated by Sica et al. (2023), who found that by acidifying the DSF from a pH of 9.1 to 3.5, the water-extractable P increased from 16% to more than 70% of the total P. In this study, the DSF was acidified to a pH of 3.2, and the resin-P increased from 14% to 59%.

MBM is a biowaste product consisting of dehydrated and ground bones, blood, and leftover meat from slaughterhouses (Christiansen et al. 2020). It contains a significant amount of carbon (approximately 40%) and nitrogen (around 10%), which are primarily derived from organic compounds found in meat and blood (Kivela et al. 2015), whereas most of the phosphorus is derived from the bones in the form of hydroxyapatite (70%–90%) (Jeng et al. 2007). Previous studies have shown that the dissolution of Ca-bound P can be favored at a pH below 4 (Sica et al. 2023; Valsami-Jones et al. 1998). This is consistent with what we found in this study, as acidification of MBM from a pH of 5.8 to 3.9 increased the resin-P from 2.3% to 83% of the total P.

In this study, the phosphorus components in both materials consisted mainly of species that can be solubilized at lower pH levels, typically below 4. Consequently, the acidification treatment performed in this study proved to be effective in solubilizing the phosphorus from both materials, in agreement with the results of Sica et al. (2023).

4.2 | Commercial Yield and Nutrient Uptake (Hypothesis 1)

The first hypothesis tested in this study was *the placement of acidified digestate solid fraction and meat and bone meal will enhance phosphorus uptake by onions and peas, leading to increased commercial yields for both crops.*

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TABLE 4 | Metal contents in dry matter (aluminum (Al), iron (Fe), cobalt (Co), copper (Cu), zinc (Zn), and cadmium (Cd)) of onion bulbs for the treatments assessed in this study.

Onion bulb	**Al**	**Fe**	**Co**	**Cu**	**Zn**	**Cd**
	(mg kg^{-1})					
N	29.6 ± 8.1	51.0 ± 5.7	0.08 ± 0.02	4.5 ± 0.4	37.3 ± 3.5	0.62 ± 0.06
TSP	54.6 ± 16	73.3 ± 11.4	0.07 ± 0.01	4.6 ± 0.6	36.1 ± 2.2	0.66 ± 0.01
Digestate solid fraction						
DAM	68.0 ± 17	83.0 ± 15	0.10 ± 0.01	5.1 ± 0.3	50.7 ± 9.0	0.83 ± 0.2
DUM	48.9 ± 10	61.7 ± 7.8	0.08 ± 0.02	5.4 ± 0.1	35.2 ± 2.2	0.51 ± 0.03
DAP	55.2 ± 15	77.2 ± 9.2	0.09 ± 0.02	5.1 ± 0.1	34.5 ± 1.2	0.67 ± 0.08
DUP	35.6 ± 11	64.0 ± 7.5	0.08 ± 0.02	4.9 ± 0.5	33.6 ± 3.3	0.57 ± 0.08
Correlation with yield	Pearson					
	−0.08	0.12	−0.11	−0.43 [P]	0.13	0.21
p value						
Acidification	—	—	—	—	—	—
Application	—	—	—	—	—	—
Interaction	—	—	—	—	—	—
Meat and bone meal						
MAM	22.5 ± 6.5 c	49.3 ± 5.0 b	0.09 ± 0.01	5.7 ± 1.1	48.9 ± 2.9	0.62 ± 0.06
MUM	27.6 ± 5.1 c	59.8 ± 5.7 b	0.06 ± 0.01	5.6 ± 0.2	47.2 ± 2.8	0.57 ± 0.05
MAP	52.4 ± 8.5 b	64.6 ± 10 b	0.10 ± 0.01	5.6 ± 0.5	39.7 ± 2.8	0.67 ± 0.03
MUP	83.5 ± 17 a	97.1 ± 15 a	0.14 ± 0.04	7.4 ± 0.9	46.4 ± 1.4	0.75 ± 0.07
Correlation with yield	Pearson					
	−0.52 [P]	−0.56 [P]	−0.53 [P]	−0.53 [P]	−0.12	−0.36
p value						
Acidification	—	—	—	—	—	—
Application	*	*	*	—	—	—
Interaction	—	—	—	—	—	—

Note: First letter = A: acidified; U: untreated; Second letter = M: mixed; P: placed. Two-way ANOVA, *p* value: >0.05; *≤0.05; **<0.01; ***<0.001; the mean is followed by the ± standard errors. Different letters indicate a significant difference between treatments (Tukey HSD < 0.05).
*P*Indicates a significant Pearson correlation.
Abbreviations: N = no phosphorus applied; TSP = triple superphosphate; DUM = DSF untreated mixed; DSF = digestate solid fraction; MBM = meat and bone meal.

Onions have a shallow and fine root system, which limits their ability to efficiently explore resources in the bulk soil (Brewster 2009). Due to this characteristic, placing a highly soluble P fertilizer close to the seeds can help the roots to access P during the early stages of growth, thereby promoting plant growth (Goswami and Kalidas-Singh 2023). For instance, Cooke et al. (1956) found that the placement of mineral P fertilizer in bands 7.5 cm below the seeds significantly increased onion yields when compared to mixed treatments at doubled application rates.

The process of nitrogen fixation in legume crops is energy-intensive and requires a high concentration of phosphorus in their nodules. As a result, legumes have a high demand for phosphorus, making P fertilization crucial for their production (Henry, Slinkard, and Hogg 1995). Phosphorus concentrations in root nodules are three times higher than in other plant organs, and this distribution ratio remains constant even under P-deficient conditions, although nodule dry weight may decrease (Powers et al. 2020; Sulieman and Tran 2015; Vadez et al. 1999). Thus, higher P availability will ensure a more efficient nitrogen fixation and plant growth. However, in this experiment, the soil was fertilized with nitrogen, and we did not assess the nitrogen fixation by the peas.

Peas are also responsive to the placement of soluble P fertilizers. Cooke (1954) found that the placement of mineral P fertilizer in bands close to the seeds considerably increased the root growth in the early stages, with a visible increase in root proliferation in the P-rich zone of the soil. Cooke's (1954) results also indicated a significant increase in grain yield when comparing the placed mineral P fertilizer with broadcasting.

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TABLE 5 | Metal contents in dry matter (aluminum (Al), iron (Fe), cobalt (Co), copper (Cu), zinc (Zn), and cadmium (Cd)) of pea grains for the treatments assessed in this study.

Pea grain	Al	Fe	Co	Cu	Zn	Cd
	(mg kg^{-1})					
N	3.2 ± 0.2	81.8 ± 3	0.10 ± 0.01	6.0 ± 0.6	47.5 ± 3.1	0.05 ± 0.03
TSP	2.8 ± 0.3	86.7 ± 5	0.14 ± 0.01	3.6 ± 0.7	56.2 ± 1.3	0.15 ± 0.02
Digestate solid fraction						
DAM	4.1 ± 0.5	59.7 ± 4	0.14 ± 0.01 ab	5.1 ± 0.1 a	53.1 ± 1.3	0.14 ± 0.01
DUM	3.2 ± 0.4	62.5 ± 5	0.10 ± 0.01 b	5.6 ± 0.2 a	49.7 ± 2.2	0.12 ± 0.01
DAP	4.3 ± 0.1	68.4 ± 6	0.15 ± 0.02 ab	3.0 ± 0.3 b	48.2 ± 1.1	0.14 ± 0.01
DUP	3.5 ± 0.5	66.6 ± 6	0.18 ± 0.02 a	3.1 ± 0.4 b	51.8 ± 2.6	0.14 ± 0.01
Correlation with yield	Pearson					
	0.16	−0.16	0.32	−0.74 *P*	−0.22	0.04
p value						
Acidification	—	—	—	—	—	—
Application	—	—	**	***	—	—
Interaction	—	—	—	—	—	—
Meat and bone meal						
MAM	2.6 ± 0.4	78.1 ± 9	0.12 ± 0.01 b	4.6 ± 1.1	55.2 ± 2.6 b	0.16 ± 0.06
MUM	6.7 ± 1.8	64.1 ± 7	0.17 ± 0.02 b	3.1 ± 0.3	56.9 ± 0.9 b	0.17 ± 0.01
MAP	2.9 ± 0.6	71.2 ± 10	0.19 ± 0.01 b	3.2 ± 0.5	52.5 ± 3.9 b	0.15 ± 0.01
MUP	5.3 ± 0.3	83.9 ± 6	0.44 ± 0.10 a	4.1 ± 0.6	70.3 ± 9.9 a	0.33 ± 0.11
Correlation with yield	Pearson					
	−0.08	−0.18	−0.42 *P*	−0.48 *P*	−0.41 *P*	−0.21
p value						
Acidification	*	—	*	—	*	—
Application	—	—	*	—	—	—
Interaction	—	—	—	—	—	—

Note: First letter = A: acidified; U: untreated; Second letter = M: mixed; P: placed. Two-way ANOVA, *p* value: >0.05; *≤0.05; **<0.01; ***<0.001; the mean is followed by the ± standard errors. Different letters indicate a significant difference between treatments (Tukey HSD < 0.05). *P* indicates a significant Pearson correlation.

Abbreviations: N = no phosphorus applied; TSP = triple superphosphate; DUM = DSF untreated mixed; DSF = digestate solid fraction; MBM = meat and bone meal.

Our results for the DSF are consistent with this. We found that the DAP significantly increased the P uptake, yield (dry weight), and fresh weight of onion bulbs by around 100% compared to the acidified DSF mixed with the top layer (DAM). In the case of peas, the DAP resulted in a P uptake, dry and fresh yields that were 60% higher than with the DAM. For both crops, the yield was also significantly increased by around 40%–60% when comparing the DUP to the DAP, indicating that the increased P solubility due to the acidification also had a significant effect on yield.

The phosphorus MFE of the DSF can be relatively high, reaching up to 80% (Brod 2018). In this study, the MFE for DUM in onion was 61%, whereas for pea, it was 88% when mixed with the soil. However, for the DAP, these values were 126% and 146% in terms of P uptake for onions and peas, respectively, making the treatments considerably more effective than the TSP. We speculate that this could be due to two reasons. The first is that the DSF contains plant nutrients other than P (Table 1). Thus, although we tried to avoid nutrient limitations by applying all essential nutrients (except P) in sufficient amounts for plant growth, we cannot exclude that other elements applied with the acidified DSF may have increased the plant growth and, consequently, the P uptake. However, we did not observe considerable differences in terms of nutrient contents between DAP and TSP (Tables 4 and 5; Tables S3 and S4). Another possibility is that the TSP was only applied mixed with the soil top layer, which may have resulted in a lower P uptake and plant growth compared to a treatment where TSP would have been applied placed close to the seeds.

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In this study, phosphorus was mixed into the top soil layer to simulate a broadcast application of mineral P fertilizer, a common agricultural practice in Denmark. As previously discussed, it is well known that crops tend to respond positively to the localized application of mineral P fertilizers (Lemming et al. 2016; van der Bom et al. 2023). Therefore, the application method of the TSP may have reduced its P uptake, which was lower than that of the DAP.

Acidification is a treatment known to effectively increase the P solubility and availability of biowastes (Fangueiro, Hjorth, and Gioelli 2015; Keskinen et al. 2023; Kopp et al. 2023; Zireeni, Jones, and Chadwick 2023). Regueiro et al. (2020) conducted a study in which they cultivated maize using untreated and acidified DSFs placed in a layer 10–12 cm below the soil surface. At 35 days after sowing, they observed that the acidified treatment significantly increased P uptake compared to the untreated treatment (from 12.5 to 18.5 mg of P per plant). However, they did not find significant differences in shoot dry matter.

This could be explained by the fact that in the early stages, crops tend to have a higher rate of P uptake than growth rate, leading to P accumulation in their tissues (Römer and Schilling 1986). For example, in the case of onions, the highest P uptake rate typically occurs around 40 DAT, whereas the highest growth rate is usually achieved between 60 and 80 DAT (Thangasamy 2016). A similar pattern is observed in peas, where the P uptake rates are higher in the first 30 days after sowing, followed by increased shoot growth after this period, which results in a decrease in P content in the shoots over time (Minář and Laštůvka 1969).

In this study, it was evident that the treatments receiving the untreated and acidified DSF placed close to the seeds followed this pattern, as at the time of harvest, the N and P contents in the shoots were relatively low. This is probably because the plants had entered the senescence stage, and most of the N and P had been transported from the shoots to the grains. Consequently, at harvest, most of the P in peas was in the grains, and no significant differences were observed in terms of P uptake in the shoots (Figure 3). It is worth noting that pot experiments, which are often conducted over short periods (i.e., 4–6 weeks) to assess different biowaste fertilization treatments and strategies, often show significant differences in terms of P uptake or P contents in the shoots. However, these experiments do not consistently observe differences in terms of shoot biomass (Christiansen et al. 2020; Lemming et al. 2016; Regueiro et al. 2020; Wang, Jensen, and Magid 2016). Therefore, on the basis of the preceding discussion, it can be assumed that higher P uptake and concentrations in the early stages are likely to result in higher yields at harvest and can be considered better parameters for assessing fertilizer efficiency.

For MBM, the following treatments showed significantly higher yields and P uptake compared to the untreated placement: AM, AP, and UM. Notably, the MUP treatment showed significantly lower yields even compared to the negative control, suggesting that it may have had a toxic effect on the plant, reducing yield, as illustrated in Figure 1. In previous studies, we have demonstrated that placing MBM in the soil creates an ammonium toxicity zone, inhibiting root growth within a 20–30 mm radius around the placement zone (unpublished data). As shown by Sica et al. (2023), when untreated MBM is placed in the soil, P diffusion is limited to a distance of 2–3 mm from the placement zone. In contrast, acidified MBM allows P diffusion to cover significantly greater distances, further than the aforementioned toxicity zone. On the basis of this, we hypothesize that the ammonium toxicity zone restricts root growth and access to P from untreated MBM because the roots cannot reach the placement zone. In the case of acidified MBM, the P can diffuse beyond the toxicity zone, enabling the plant to access it. Moreover, as we found that for the MUP, plant growth was even lower than in the negative control, and phosphorus limitation was most probably not the only factor constraining growth. It is known that ammonium toxicity has other negative side effects that stress the plant and inhibit growth, such as the inhibition of cation uptake (K^+, Ca^{2+}, and Mg^{2+}), intracellular alkalinization, extracellular acidification, disruption of hormonal homeostasis, increased oxidative stress, and high energy costs to maintain low levels of cytosolic NH_4^+ content (Esteban et al. 2016).

Therefore, our findings for the DSF confirm our first hypothesis, as the placement of the acidified DSF significantly increased the P uptake and the commercial yield of onions and peas. However, this was not the case for the MBM, as the acidified MBM mixed and placed did not differ significantly from the MUM with the soil.

4.3 | Elemental Content in Bulbs and Grains Dry Matter (Hypothesis 2)

The second hypothesis tested in this study was that *the acidification will not only solubilize phosphorus but also undesirable elements (i.e., Cd, Cu, Al), potentially increasing their dry matter contents in the edible parts of onions and peas.*

Both materials used in this study had significantly lower Cd, Cr, Cu, and Zn contents (Table 1) compared to the limits set by the Danish executive order for the use of wastes for agricultural purposes (Miljøstyrelsen 2018). The limits for heavy metal content in wastes to be applied as fertilizers are as follows: Cr = 100 mg kg^{-1}; Cu = 1000 mg kg^{-1}; Zn = 4000 mg kg^{-1}; and Cd = 0.8 mg kg^{-1}. The soil used in this study also had Cd, Cr, Cu, and Zn contents (Table 1) considerably lower than the limits set by the Danish ministry: Cr = 30 mg kg^{-1}; Cu = 40 mg kg^{-1}; Zn = 100 mg kg^{-1}; and Cd = 0.5 mg kg^{-1} (Miljøstyrelsen 2018). Thus, both the metal contents in the soil and the materials used in this study are below the threshold values suggested for lower environmental and health risks.

Increased levels of undesirable elements in the edible parts of onions and peas may lead to a higher daily intake of heavy metals (Marini et al. 2021), such as copper and cadmium. This elevated intake could potentially result in short- and long-term adverse effects on human health, including conditions such as diabetes, cancer, renal dysfunction, and osteoporosis (Schaefer, Dennis, and Fitzpatrick 2020). Our results, however, indicate that the contents of Al, Fe, Co, Cu, Zn, and Cd were little or not affected by the acidification and the placement of DSF and MBM. In fact, in onion bulbs and pea grains, the levels of Fe, Co, and Cd were considerably higher for the untreated MBM placed, as these metal contents were usually negatively correlated with yield (Tables 3 and 4; Figure S1). This can be explained by the "dilution

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effect in plant nutrition," as in plants with higher yields, the nutrients and other elements can be diluted due to the higher content of carbohydrates (carbon, oxygen, and hydrogen) (Jarrell and Beverly 1981). The onions fertilized with acidified DSF placed had a larger diameter (Figure 1; Table S1), and the peas also tended to have more grains per plant for this treatment (Tables S1 and S2). Thus, the placement of acidified DSF significantly increased the yield without increasing the content of undesirable elements.

The application method and acidification also had minimal or no effects on the contents of macronutrients and micronutrients in onion bulbs and pea grains, including nitrogen (protein/amino acids) (Wu 2016), phosphorus (Calvo, Moshfegh, and Tucker 2014), potassium (He and MacGregor 2008), calcium (Li et al. 2018), and zinc (Chasapis et al. 2012), which are essential and beneficial for human health. In our study, calcium was the only element with a positive correlation with yield. In legumes, this positive correlation between calcium content in the grains and yield has also been observed in other studies (Ribeiro et al. 2013; Sica et al. 2021). According to Domingues et al. (2016), the increase in calcium concentration in the grains is related to a high calcium bioavailability in the soil. In our study, both materials had high calcium contents (Table 1), and the acidification may have dissolved this calcium, making it also more available to the plant. This is confirmed by the fact that, for pea, the acidification had a significant effect on calcium uptake on grains and shoots.

Previous studies have shown that phosphorus fertilization and placement of mineral phosphorus fertilizers have no effect on the nutritional quality of pea grain, especially in terms of protein content (Gubbels 1992; Henry, Slinkard, and Hogg 1995). However, in our study, for peas, the placement of DSF untreated and acidified led to a significant reduction in N and P contents in the grains, as these elements were negatively correlated with yield. This may indicate that for pea, these elements are affected by the dilution effect previously discussed (Jarrell and Beverly 1981), which is known to occur frequently in legumes, as the yield is negatively correlated with protein content (Sica et al. 2021), which indicates that increasing yield in legumes may imply in a commercial production with lower protein content.

Therefore, on the basis of our results and the previous discussion, our second hypothesis can be rejected. Although the acidification may increase the solubility of undesirable elements, the increased P solubility increased the P uptake and commercial yields of both crops, which diluted the element contents in the dry matter of the bulbs and grains, resulting in no significant difference to the untreated treatments.

5 | Conclusions

In conclusion, the acidification process effectively increased phosphorus solubility from both materials; however, it did not necessarily result in an increase in P availability for MBM. Regarding our first hypothesis, the placement of acidified DSF significantly increased phosphorus uptake and commercial yields for both crops. However, this effect was not observed for acidified MBM, indicating a nuanced response influenced by the specific material composition, probably a high nitrogen content, which may have created an ammonium toxicity zone around the placement area, inhibiting plant growth.

Concerning our second hypothesis, which suggested an increase in the dry matter contents of undesirable elements (Cd, Cu, Al) due to acidification, our findings contradicted this assumption. The increased P solubility associated with acidification led to higher P uptake and commercial yields, diluting the concentrations of undesirable elements in bulbs and grains. Notably, the content of undesirable elements did not significantly differ from the untreated treatments, except for MBM, where the untreated material placed had significantly lower yields and higher element contents in dry matter for both crops.

These results highlight the complexity of nutrient interactions and emphasize the importance of considering both material characteristics and crop responses in biowaste application strategies. Therefore, the placement of acidified DSF can increase its P fertilizer value, with no effects on the contents of undesirable elements in the dry matter of pea grains and onion bulbs.

Acknowledgments

This project has received funding from the "*European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No.860127*".

Data Availability Statement

The data that support the findings of this study are openly available in the Electronic Research Data Archive from the University of Copenhagen. A link with DOI will be provided after acceptance.

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