Received: 28 January 2024 | Revised: 7 February 2025 | Accepted: 9 February 2025

DOI: 10.1111/sum.70039

REVIEW ARTICLE

Soil Use and Management | BRITISH SOCIETY OF SOIL SCIENCE | WILEY

Strategic placement of mineral and biobased fertilizers for optimizing phosphorus use efficiency: A comprehensive review

Pietro Sica[1,2] | Tomas Javier Sitzmann[3] | Dorette Müller-Stöver[1] | Jakob Magid[1]

[1]Department of Plant and Environmental Sciences, University of Copenhagen, Frederiksberg, Denmark

[2]Department of Food Science and Technology, College of Agriculture 'Luiz de Queiroz', Piracicaba, São Paulo, Brazil

[3]Department of Agricultural, Forestry, and Food Science, University of Turin, Turin, Italy

Correspondence
Pietro Sica and Jakob Magid, Department of Plant and Environmental Sciences, University of Copenhagen, 40 Thorvaldsenvej, 1871 Frederiksberg, Denmark.
Email: pietro@plen.ku.dk and jma@plen.ku.dk

Funding information
Danmarks Frie Forskningsfond; H2020 Marie Skłodowska-Curie Actions

Abstract

This study presents a literature review focusing on the placement of phosphorus-rich fertilizers, evaluating their agronomic efficiency and potential benefits to plant growth. While the placement of mineral phosphorus fertilizer offers benefits such as increased early season phosphorus uptake and higher yields, the success of this practice is strongly influenced by factors such as soil type, weather conditions, production system, application depth and others. However, the placement of biowaste and biobased fertilizers can have drawbacks. This review highlights the negative effects associated with the placement of biobased fertilizers, primarily due to low phosphorus solubility and unbalanced nutrient composition, resulting in reduced reactivity and potential ammonium toxicity. Strategies to mitigate these limitations are discussed, including acidification to increase phosphorus solubility and recommending specific placement distances and timing to minimize toxicity effects. In addition, this study demonstrates the importance of further studies on this topic and propose the use of novel visualization techniques (planar optodes, diffusion gradient in thin films) to elucidate the effects of placement of different biowastes on physical, chemical and biological processes in the placement zone and surrounding soil. This will enable a comprehensive understanding of fertilizer composition and placement strategies to unlock the full potential of biobased fertilizers, improve their P use efficiency in agriculture and thus contribute to sustainable agricultural practices and increased productivity, in line with several of the United Nation's Sustainable Development Goals.

KEYWORDS

band application, biowastes, DGT, nutrient cycling, planar optodes, starter fertilizer

1 | INTRODUCTION

More efficient use and land application of societal resources is critical for sustainable food production and mitigating negative environmental impacts. This is in line with the United Nations Sustainable Development Goals 1 (zero poverty), 2 (zero hunger), 6 (clean water and sanitation), 11 (sustainable cities and communities), 12 (responsible consumption and production), 13 (climate action), 14 (life under water) and 15 (life on land). The 4R Nutrient Stewardship guidelines were developed by the fertilizer industry to improve nutrient use efficiency and emphasize that fertilizers should be applied at the right time, in the right place, at the right rate, and with the right nutrient sources (Johnston & Bruulsema, 2014).

The placement of P-rich fertilizers as starter fertilizers is a strategy that can increase their agronomic efficiency (Makaza & Khiari, 2023; Nkebiwe et al., 2016; Sandral et al., 2019). It involves placement of the P fertilizer close to the seeds (right place) (Grant et al., 2001), which creates a P-rich patch in the soil that may provide a greater amount of P to the crops at early stages (right time) (Lemming et al., 2016). The root response to nutrient-rich patches has been the subject of extensive research, exemplified by early work by Cooke already in the 1940s-50s (Cooke, 1949a, 1949b, 1951, 1954; Cooke et al., 1956; Warren et al., 1958; Widdowson & Cooke, 1958) and Drew in the 1970s (Drew, 1975). A number of advantages of placement of mineral P fertilizers have been proposed, such as reducing the contact area of P with the soil, providing more P in the early season (Grant et al., 2001), stimulating root growth in P-rich areas (Hodge, 2004) and establishing competitive advantages against weeds (Robinson et al., 1999).

However, factors such as the choice of the right fertilizer source and appropriate application rates can significantly influence the agronomic efficiency of placing P fertilizers. For example, despite the previously mentioned advantages of placing mineral fertilizers, our ongoing studies and recent literature consistently reveal potential negative impacts associated with placing biowastes and biobased fertilizers (Baral et al., 2021; Pedersen et al., 2020; Sica, Kopp, Magid, & Müller-Stöver, 2023). One limiting factor is that these materials typically have low or no soluble P, which may not supply sufficient P to meet the plant's demand (Lemming et al., 2016). Another factor related to the composition of biowastes and biobased fertilizers that may limit the benefits of placement is the unbalanced nutrient concentrations. As a consequence, nutrients and harmful elements can be under- or overapplied in the placement zone, limiting plant growth and/or causing toxicity effects (Ali et al., 2011; Hoque et al., 2008; Imadi et al., 2016; Pan et al., 2016).

Despite the existence of detailed work related to the placement of mineral fertilizers (Cooke, 1949a, 1954; Cooke et al., 1956; Hodge, 2004; Robinson, 1994; Robinson et al., 1999; van der Bom, Williams, Borrell, et al., 2023; van der Bom, Williams, Raymond, et al., 2023) and, more recently, a growing focus on biobased fertilizers (Baral et al., 2021; Lemming et al., 2016; Pedersen et al., 2017; Sica, Kopp, Magid, & Müller-Stöver, 2023; Wang et al., 2016), we have identified a lack of critical reviews assessing the potential use of placement of biobased fertilizers as a strategy to increase their P use efficiency. To address this, we conducted a comprehensive review of the literature addressing:

1. The main mineral and biobased P fertilizers and a description of some of their most relevant characteristics (e.g. P solubility);
2. the benefits and the factors affecting the placement of P fertilizers and which environmental conditions favour this practice;
3. the main limiting factors for the placement of biobased fertilizers to increase P use efficiency;
4. agronomic strategies to mitigate negative effects and enhance phosphorus availability in the placement zone of biobased fertilizers;
5. the use and development of new techniques and methodologies for in-depth studies of biogeochemical processes in the placement zone and surrounding soil.
6. Finally, we present a short experimental study in the context of this review.

2 | P FERTILIZERS

2.1 | Sources

Phosphorus is a macronutrient essential for plant growth and constitutes one of the main limiting factors for crop productivity in global agriculture (Kvakić et al., 2018). When applied to the soil, phosphorus can be immobilized by microorganisms (Richardson & Simpson, 2011) or bound by metals such as aluminium, iron and calcium, reducing its availability to plants (Hedley & McLaughlin, 2005). Consequently, the phosphorus use efficiency from fertilizers is relatively low in the short-term, ranging from 7.5% to 12.4% for mineral fertilizers (Schütz et al., 2018; Yu et al., 2021), but can reach values up to 50%–70% in the long-term, due to the residual effects (Roberts & Johnston, 2015).

Mineral phosphorus fertilizers are derived from phosphate rock, which is a nonrenewable resource listed by the European Commission as a critical raw material (European Comission, 2017). This designation is due to uncertainties regarding its use and availability in the coming decades (Geissler et al., 2018). Moreover, mineral P fertilizer prices have increased considerably in recent years, exacerbated by conflicts between Russia and Ukraine (Ibendahl, 2022). On a positive note, the higher cost of mineral fertilizers provide an opportunity for the adoption of biobased fertilizers (BBFs) by farmers (Moshkin et al., 2023).

Wester-Larsen et al. (2022) defined biobased fertilizers (BBFs) 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 fertilizer for crops*'. This review will adopt this definition to refer to materials of biological origin that contain nutrients and are applied as fertilizers to agricultural fields, hereafter called 'biobased fertilizers' or 'BBFs'. It is worth noting that BBF does not necessarily contain organic carbon, as in the case of incineration ashes (Kopp, Sica, Lu, et al., 2023).

A study by Recena et al. (2022) demonstrated that a better allocation and more precise application of recycled P resources could cover most of the European Union's P demand with a circular economy approach, thereby reducing dependence on the imports of mineral P fertilizers. Animal-derived organic residues (e.g. slurry, manure, meat and bone meal) and municipal organic residues (sewage sludge) constitute the majority of phosphorus flows in the European Union member states. Consequently, regions characterized by dense urbanization and significant animal production generate substantial amounts of residues, resulting in a surplus of phosphorus and other nutrients (van Dijk et al., 2016).

Denmark, for instance, imports 12,000 tons of total P as mineral fertilizer per year (Klinglmair et al., 2015) and is characterized by a large animal production, leading to a P surplus of 7 kg of total P per hectare per year (Thorsøe et al., 2022). Therefore, better allocation and more precise application of P-rich resources are crucial to reduce agricultural dependence on imports of mineral P fertilizers and to mitigate negative environmental impacts resulting from the surplus and overapplication of P from organic residues.

2.2 | Composition and P availability

The pH, total N, total P, water-extractable P, and bicarbonate-extractable P of relevant mineral P fertilizers and P-rich biobased fertilizers are presented in Table 1. Mineral fertilizers are typically formulated to achieve high P contents and high levels of soluble phosphorus, as in the case of triple superphosphate as well as mono- and diammonium phosphates (Hedley & McLaughlin, 2005). These characteristics facilitate logistics and increase the interest of farmers, as higher solubility often indicates higher fertilizer use efficiency. Therefore, farmers would be willing to pay higher prices for the same amount of nutrients in mineral fertilizer compared to a biobased fertilizer (Moshkin et al., 2023; Slavík et al., 2019; Tur-Cardona et al., 2018).

In the case of biobased fertilizers, the low nutrient concentration in terms of fresh weight and high volumes are two of the main barriers to a better allocation of these resources from the area where they are generated to agricultural fields (Slavík et al., 2019). Furthermore, factors related to the composition of biobased fertilizers affect their agronomic efficiency and can act as a barrier to adoption by farmers (Case et al., 2017). These factors are highlighted in Table 1.

As can be seen in Table 1, the composition of the same biowaste varies considerably. A limiting factor is that BBFs usually have an unbalanced N:P ratio (Table 1), and in the absence of regulations on the amounts of P to be applied, farmers tend to apply the fertilizers based on the crop's nitrogen demand (Prado et al., 2022). As a result, overapplication of phosphorus may occur, potentially saturating and accumulating P in agricultural soils and posing a threat to water bodies through eutrophication (Fischer et al., 2017).

Biobased fertilizers also contain other elements that can react with phosphate, such as Ca, Fe and Al, reducing the solubility and availability of P to the crop (see Table 1). Consequently, the phosphorus efficiency of biobased fertilizers is relatively low compared to mineral fertilizers (Möller et al., 2018). These biowastes can also undergo thermal treatment to reduce volume, increase P concentration (see Table 1), mitigate pathogens and generate energy (Mininni et al., 2015). In the case of pyrolysis, the formation of recalcitrant carbon can contribute to soil carbon sequestration and climate change mitigation (Smith, 2016). However, thermal treatments reduce P solubility (see Table 1) and availability due to the formation of more recalcitrant and insoluble P species (Kopp, Sica, Magid, & Muller-Stover, 2023; Nanzer, Oberson, Berger, et al., 2014; Nanzer, Oberson, Huthwelker, et al., 2014).

The factors highlighted above are not only major drawbacks for the agricultural use of biobased fertilizers, but also affect the interactions between roots and fertilizers in the placement zone. These effects are discussed in more detail in the following sections.

3 | FERTILIZER PLACEMENT

3.1 | Types of fertilizer placement

In this review, we define the placement of fertilizer as '*fertilizer application methods into a specific spot, aiming to reduce the contact area of the fertilizer with the soil, with the crop row as a reference position*'. Figure 1 shows the main types of placement under field conditions and in controlled experiments (pot/rhizobox).

TABLE 1 Chemical composition (pH, total nitrogen and phosphorus, water-extractable phosphorus and bicarbonate-extractable phosphorus) of some mineral and biobased fertilizers.

Fertilizer	pH	Total N	Total P	WEP	$NaHCO_3$-P
		($g\,kg^{-1}$ DM)		(% of total P)	
Mineral fertilizers					
Triple superphosphate[a]	1.5	—	200	Highly soluble	
Monoammonium phosphate[a]	3.5	120	230		
Diammonium phosphate[a]	7.5-8.0	180	204		
Biobased fertilizers					
Sewage sludge	7.2–8.3[b,c]	19–52[b]	11–43[b,c]	0.8–12[c]	3.5–22[b]
Sewage sludge ash	7.5–10.1[c,d,e]	—	76–110[c,e]	0.003–0.06[c]	0.9[d,e]
Sewage sludge biochar	7.7–10.1[e,f,g]	14–64[f,g]	39–101[f,g,h]	0–0.5[f,h]	0.5–0.7[e,f]
Pig slurry	6.7–8.2[i,j,k,m]	20–97[i,j,k,l,m]	8.8–21[i,j,k,l,m]	13–21[k,l,m]	20
Cattle manure	7.1–8.6[i,m]	19–43[i,m]	3.1–18[i,m]	48–80[m,n]	60–80[m,n]
Digestate solid fraction	9.1[d,k]	20–36[d,k]	26–36[d,k]	11–17[d,k]	31[d]
Meat and bone meal	5.5–6.2[d,o]	30–120[d,o,p]	22–97[d,o,p]	3.7–11[d,o,q]	9.1–16[d,o,q]
Meat and bone meal ash	6.7[r]	0–1.7[r,s]	78–189[r,s]	—	—
Meat and bone meal biochar	11.2[e]	52[e]	107[e]	0.3[e]	1.0[e]
Poultry litter	6.7–7.2[o,t]	30.6–45[o,t]	10–15[o,t,u]	16–80[o,t,u]	23.7[o]
Poultry litter ash	12.4[e]	—	58–68[e,v]	0.2[e]	1.6[e]
Poultry litter biochar	9.5–11.5[u,w]	1.2–42[u,w]	22.7–30.5[u,w]	1–6[u,w]	—

[a]Hedley and McLaughlin (2005).
[b]Øgaard and Brod (2016).
[c]Lemming et al. (2020).
[d]Sica, Kopp, Magid, and Müller-Stöver (2023).
[e]Kopp, Sica, Lu, et al. (2023) and Kopp, Sica, Magid, and Muller-Stover (2023).
[f]Unpublished.
[g]Liu et al. (2019).
[h]Yuan et al. (2016).
[i]Prado et al. (2022).
[j]Antezana et al. (2016).
[k]Regueiro et al. (2020).
[l]Roboredo et al. (2012).
[m]Ylivainio et al. (2021).
[n]Chapuis-Lardy et al. (2003).
[o]Brod, Øgaard, Hansen, et al. (2015) and Brod, Øgaard, Haraldsen, and Krogstad (2015).
[p]Möller et al. (2018).
[q]Christiansen et al. (2020).
[r]Leng et al. (2019).
[s]Coutand et al. (2008).
[t]Keskinen et al. (2023).
[u]Song and Guo (2012).
[v]Bauer et al. (2019).
[w]Wang et al. (2015).

The fertilizer placement in bands (stripes) can be done along the seed row in different ways (Makaza & Khiari, 2023). As illustrated in Figure 1a, the fertilizer bands can be placed as follows: (i) in the seed row as a starter fertilizer (Drazic et al., 2020; van der Bom, Williams, Borrell, et al., 2023); (ii) in the subsurface (Farmaha et al., 2011); (iii) on the side of the seed row at different depths or as side-dress (Makaza & Khiari, 2023; Messiga et al., 2020); (iv) transplanting placement. The latter can be achieved by transplanting crops together with the substrate (enriched with fertilizer) (Mogren et al., 2008) or by direct application in tree pits (holes) in orchards (Ovalle et al., 2016) or in planted forests for bioenergy and timber production (Fernandez et al., 2000).

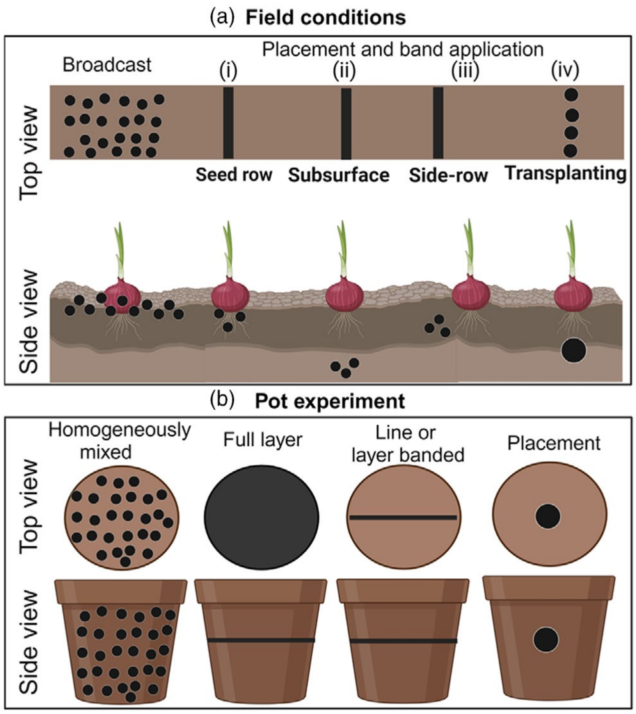


FIGURE 1 Overview of different fertilizer application methods under field conditions (a) and in pot experiments (top and side view) (b), highlighting different placement methods: (i) band, furrow, or seed row; (ii) subsurface band; (iii) side-row band; (iv) transplanted or 'spot' placement. Adapted from Drazic et al. (2020) and Makaza and Khiari (2023) for field application. For pot experiment (and rhizoboxes) adapted from Baral et al. (2021) and van der Bom, Williams, Borrell, et al. (2023).

The optimal type of placement depends on the field slope, equipment availability, the crop, management system, environmental conditions, soil type and the physical structure of the fertilizer. The first three placement methods are typically performed with solid fertilizers, in the form of granules (de Castro et al., 2023), pellets (Delin et al., 2018), or liquid fertilizers such as animal slurry, injected in bands in the subsurface or applied superficially in strips (Fangueiro et al., 2018). The efficiency of each placement method depends on the fertilizer source and application rate, which will be discussed in the following sections.

Pot and rhizobox experiments are usually conducted for short periods of time, aiming to determine the P availability of different biowastes (Bogdan et al., 2023), to compare alternative fertilizers as a replacement for a mineral fertilizer source (Ashekuzzaman et al., 2021), or to assess the effects of different treatments and application methods on the fertilizer efficiency (Kopp, Sica, Lu, et al., 2023; Sica, Kopp, Magid, & Müller-Stöver, 2023; Wang et al., 2016). The placement method in these controlled experiments is usually done in three different ways (Figure 1b): (i) the fertilizer is applied in a full layer between two soil columns, ensuring full contact with the soil surface above and below the fertilizer (see: Christiansen et al. (2020) and Pan et al. (2016)); (ii) application in lines or strips simulating band application (see Baral et al. (2021) and Pedersen et al. (2017)); (iii) placement, with the application being limited to a specific spot in the soil (see Lemming et al. (2016)).

However, controlled experiments rarely compare different application methods (Lemming et al., 2016; van der Bom, Williams, Borrell, et al., 2023; van der Bom, Williams, Raymond, et al., 2023; Wang et al., 2016) and the fertilizers are usually applied 'homogeneously mixed' with the soil. Sica, Kopp, Magid, and Müller-Stöver (2023) discussed that homogeneous fertilizer distribution is a laboratory construct that cannot be obtained in the field situation. If the fertilizer reaction with the soil leads to solubilization of P, this can lead to overestimation of fertilizer efficacy. Although the broadcast application of fertilizers aims at a homogeneous distribution over the field before or during sowing (see Figure 1), it is worth noting that the broadcast application of mineral and biobased fertilizers often results in a heterogeneous distribution of resources, forming nutrient-rich patches in the soil (Hodge, 2004). Therefore, whether by design or by chance, the interaction between soil and fertilizer is typically confined to discrete bands or patches at a well-defined depth, influenced by tillage (Magid et al., 2006). Thus, these factors highlight the importance of studying soil-fertilizer interactions in nutrient-rich patches, even when considering a 'uniform' broadcast application.

3.2 | Benefits and factors affecting the mineral P fertilizer placement

The placement of mineral phosphorus as a starter fertilizer has been proposed as a practice in line with two of the guidelines of the 4R Nutrient Stewardship: the right place and the right time (Johnston & Bruulsema, 2014; Makaza & Khiari, 2023). The placement of phosphorus fertilizer can: (i) increase the phosphorus use efficiency of mineral fertilizers (Nkebiwe et al., 2016); (ii) provide higher amounts of phosphorus and improve the establishment of the crop at an early stage (van der Bom, Williams, Borrell, et al., 2023); (iii) promote plant and root growth (Lemming et al., 2016; van der Bom, Williams, Borrell, et al., 2023; van der Bom, Williams, Raymond, et al., 2023); (iv) ultimately lead to increased yield (Quinn et al., 2020). In Figure 2, we outline the primary potential advantages of the placement of P-rich fertilizers over broadcast application.

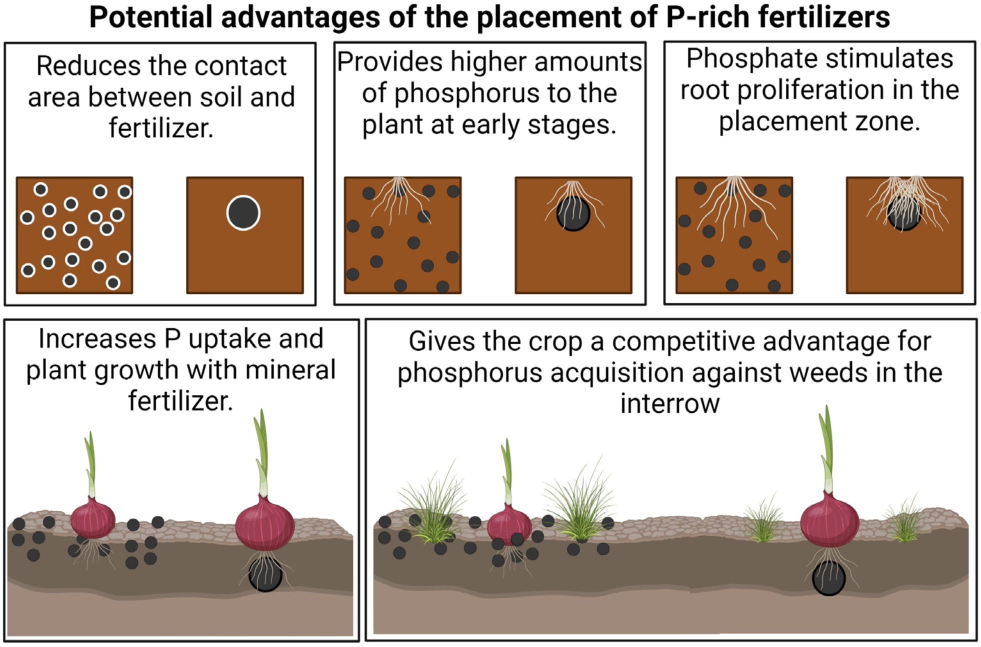


FIGURE 2 Illustration of the potential advantages of the placement of P-rich fertilizers compared to the broadcast application.

3.2.1 | Effects of placement on root architecture, plant growth and yield

Root plasticity allows plants to adapt to various growth-limiting abiotic and biotic factors in the soil (Suralta et al., 2018), including P acquisition (Wang et al., 2021). It is well documented in the literature that plants tend to allocate root growth to phosphate-rich areas of the soil (Drew, 1975; Ho et al., 2005; Hodge, 2004; Lemming et al., 2016; Li et al., 2014; Ma et al., 2016; Mollier & Pellerin, 1999; Robinson, 1994; Thorup-Kristensen, 2006; van der Bom, Williams, Borrell, et al., 2023; van der Bom, Williams, Raymond, et al., 2023). The higher root proliferation in the placement zone is illustrated in Figure 2.

This plant adaptive strategy enhances phosphorus uptake efficiency and soil resource exploration, potentially providing a competitive advantage for the crop over weeds (Robinson et al., 1999). For this reason, the placement of mineral P fertilizer is also considered an efficient non-chemical weed control method (Karamanos et al., 2002; Naderi & Bijanzadeh, 2015). Blackshaw and Molnar (2009) investigated the impact of various P fertilizer application methods on weed and wheat growth. They found that weed biomass and P uptake were lower when P fertilizers were seed-placed or subsurface-banded compared to the surface-broadcast application method. In Figure 2, the rationale for this advantage is illustrated. In the case of row crops, these benefits of placement may be further enhanced (McCollough et al., 2020), as with the broadcast application, both total and labile P are more evenly distributed across the field (de Oliveira et al., 2022), providing weeds with access to labile P in the inter-row.

The placement of mineral P fertilizers has also proven effective in increasing commercial yield, as demonstrated in various meta-analyses by Freiling et al. (2022), Nkebiwe et al. (2016) and Quinn et al. (2020). The application of the right source (soluble P), at the right time (starter fertilizer), and in the right place (in the seed row) provides a greater amount of P to the crop during the early stages, as illustrated in Figure 2. This, in turn, increases the P uptake in the early growth stages, promoting higher growth rates and an accumulation of a P reserve in the shoots, which will enhance the likelihood of achieving higher yields (Minář & Laštůvka, 1969; Romer & Schilling, 1986; Thangasamy, 2016). Romer and Schilling (1986) demonstrated that when wheat shoots had developed 20%–35% of the total dry matter, 50%–60% of the total crop P uptake had already been taken up by the plant. In onion, for example, the peak of P uptake is usually around 40 days after emergence, whereas the highest growth rates are achieved between 60 and 80 days after emergence (Thangasamy, 2016). Thus, the band application of mineral P fertilizers is often recommended as a management strategy to improve the crop stand establishment at early stages, which will have positive effects on yield (Ketterings et al., 2003; Matocha, 2010; Pan & Engle, 1991). On the other hand, it has been shown by Cooke (1954) that (Cooke, 1949a, 1949b, 1951, 1954; Cooke et al., 1956; Warren et al., 1958; Widdowson & Cooke, 1958) placing mineral P fertilizers in the seed row at half the rate resulted in the same yields in horticultural crops as a full-rate broadcast application.

(Cooke, 1954). Thus, placement increases P use efficiency, allowing the farmer to apply lower rates of P.

Therefore, the placement of mineral P fertilizer is a management strategy that has demonstrated many advantages over broadcast application. However, many factors may influence the efficiency of the placement. These factors are listed and discussed in the following subsection.

3.2.2 | Factors influencing P availability and diffusion from placement zone

The placement of P fertilizers creates a nutrient-rich zone in the soil, reducing the contact area of the fertilizer labile P with chemical compounds in soil (Figure 2), such as aluminium and iron oxides and calcium (Grant et al., 2001). Thus, the soil physical and chemical properties will have a strong influence on the efficiency of fertilizer placement and P availability (Graham et al., 2002; Meyer et al., 2020, 2021). The band application of P fertilizer is a management practice adopted in weathered soils with high P-sorption capacity (Sanchez & Uehara, 1980). In an Oxisol with low available P in Brazil, placement of triple superphosphate increased the yield of cowpea and maize by up to 50% and 100%, respectively, compared to broadcast application of the same rates (Smyth & Cravo, 1990). de Castro et al. (2023) also found that the subsurface band application of mineral fertilizer increased sugarcane yield by up to 33% in two Oxisols in Brazil. Thus, it is expected that the effectiveness of mineral P fertilizer placement will be higher in highly sorbing soils than in sandy and weakly P-sorbing soils (Sleight et al., 1984).

The spatial distribution of total and labile P in the soil also influences root access to this nutrient (Schachtman et al., 1998). de Oliveira et al. (2022) applied different mineral P sources in concentrated bands within the seed row of the crop, as well as through broadcast application in an Oxisol. They analysed the total P in soil samples collected from various depths and increasing distances from the row to create a spatial distribution of total P. Their findings indicated that, for broadcast application, the gradient of total P and available P remained restricted to the top 5 cm of the soil but distributed throughout the field. For the placement in bands, the gradient of both total P and available P expanded to a depth of 10 cm and reached 10 cm on both sides of the band. The different P distribution will also affect the P losses to the environment, as in areas with intense slope the band placement of P fertilizers (especially in the subsurface) will increase P retention in the soil and reduce P movement with runoff (Kar et al., 2012; Watts et al., 2015), thereby decreasing the risk of eutrophication of water bodies (Fischer et al., 2017).

The P diffusion in the soil is affected by several factors, including soil properties (Meyer et al., 2023), as demonstrated by Degryse and McLaughlin (2014). Their results showed that, after 28 days, the P from one monoammonium phosphate granule diffused up to 32 mm in a weakly P-sorbing soil (Alfisol). Considerably lower diffusion rates were observed in soils with amorphous oxides (Oxisol, 9.6 mm) and in a calcareous soil (10.7 mm).

Soil moisture is another key factor influencing P diffusion and availability. Drier soil conditions result in lower P diffusion and availability both in the placement zone and its surrounding soil (Bhadoria et al., 1991; Mahtab et al., 1971). This further supports the preference for placement in clay soils over sandy soils, as sandy soils typically have a lower water-holding capacity, making them more prone to moisture content fluctuations and drying in the surface layers, ultimately limiting plant access to phosphorus from the placement zone (Randall & Hoeft, 1988). To reduce the effects of moisture content at the soil surface, subsurface band application (20–40 cm) is recommended (Sandral et al., 2019), especially in tropical countries with long dry seasons, such as Australia (Singh et al., 2005) and Brazil (Coelho et al., 2021).

Colder temperatures result in reduced P diffusion (Barrow, 1983) and reaction rates with the soil (Bramley et al., 1992). Moreover, under colder conditions, root growth rates are lower, leading to reduced exploration of resources from the bulk soil (Mackay & Barber, 1984). Therefore, the placement of mineral P fertilizers tends to be favourable under colder conditions. Sheppard and Racz (1985) conducted a comparison of broadcast and placement application methods in wheat at 10°C, 15°C, 20°C and 25°C. Placement proved to be more efficient than broadcast at 10°C in terms of root proliferation in the placement zone, P uptake from the fertilizer, and overall plant growth. However, at 25°C, there was almost no placement effect and no differences in terms of P uptake from the fertilizer. In regions where crops are planted during cold winters (subtropical climate) and early springs (temperate climate), the soil temperature will be low, reducing root growth rates and limiting plant access to P in deep soil layers, typically causing P deficiency. Thus, the placement of mineral P fertilizers can be a strategy for better P uptake and management (Grant et al., 2001; Grant & Flaten, 2019).

The P solubility of the fertilizer and the amount of P applied also influence the P availability and diffusion rates from the placement zone through the soil (Meyer et al., 2023). Results from Sica, Kopp, Magid, and Müller-Stöver (2023) showed that the amount of water-soluble P in the fertilizer is significantly correlated with the amount of P released from the placement zone. As a result, for the same amount of total P applied, the diffusion rates will be higher for fertilizers with higher P solubility. In a study assessing six increasing P application rates of ammonium phosphate (highly soluble) in three different soils, Eghball et al. (1990) found that the diffusion distances were significant and positively correlated with application rates.

However, regardless of the soil type, the management strategies and available P on the soil surface may influence the effectiveness of the placement. For instance, even in highly P-sorbing soils, if the labile P in the soil surface is high due to long-term mineral P fertilizer application, band placement may not have a positive effect compared to broadcast superficial application (Nunes et al., 2020, 2021; Rosendo dos Santos et al., 2018; Stecker & Brown, 2001). It is worth noting that even with the potential benefits of mineral P fertilizer placement discussed in this section, farmers may prefer broadcast superficial application, especially in areas with high labile P in the soils (de Oliveira et al., 2022). For farmers, superficial broadcast application facilitates logistics in the field, as it can be accomplished more easily with the machinery available to them and provides greater flexibility in terms of application time (Caires et al., 2017; Corrêa et al., 2004; Olibone & Rosolem, 2010).

In summary, the effectiveness of the placement of mineral P fertilizers depends on soil properties, climatic conditions, management practices, and fertilizer composition. The main factors are: (i) soil P-sorption capacity; (ii) labile P content in the soil upper layer; (iii) field slope; (iv) soil water-holding capacity; (v) whether the area is prone to long dry periods; (vi) soil temperature; (vii) band application depth; (viii) amount of P applied; and (ix) P solubility of the fertilizer.

4 | PLACEMENT OF P-RICH BIOBASED FERTILIZERS

Despite the potential advantages of placing mineral P fertilizers discussed in the previous section, the placement of biobased fertilizers may have little or no effect on P uptake and plant growth. In fact, in some cases, it can cause toxicity, thereby reducing plant growth. The main reasons for this are low or no phosphorus solubility (Table 3) and unbalanced nutrient contents, especially the N:P ratios (Table 1; Figure 4). These factors are further discussed in the following subsections.

4.1 | P solubility

4.1.1 | Thermally treated biobased fertilizers with very low P solubility

Soil patches with more phosphate in solution attract root growth (Drew, 1975). For thermally treated biobased fertilizers (ashes and biochar), the placement zone will have little or no soluble P (Table 1), resulting in limited attraction of root growth (Bornø et al., 2023; Lemming et al., 2016) (Table 2).

Bornø et al. (2023) used novel visualization techniques to assess biogeochemical interactions in the placement zone of sewage sludge biochar in a rhizobox setup. They observed that the placed biochar appeared to be inert, showing no visible effect on root growth. Additionally, there was a reduction in alkaline and acid phosphatase activity compared to the surrounding soil, as observed by zymography. The biochar had a minimal effect on pH, as measured by planar optodes, and showed no impact on labile P in the placement zone and surrounding soil, as determined by Diffusive Gradients in Thin Films (DGT) (Table 2).

In a study by Lemming et al. (2016), the effects of mixing and placing sewage sludge ash in the soil were compared. No differences were observed in terms of root growth in the placement zone of sewage sludge ash, indicating that it was also inert in the soil. However, the placement of sewage sludge ash led to overall reduced root and plant growth, as well as decreased P uptake by maize. In the case of fertilizers with low soluble P, such as sewage sludge ashes and biochar, the application mixed with the soil increases the contact area of the fertilizer with the soil and, consequently, the P reactivity, which may increase the P availability (Müller-Stöver et al., 2021; Raymond et al., 2019).

The results of Rosendo dos Santos et al. (2018) indicated a positive response of sugarcane to the placement of triple superphosphate (highly soluble P) under field conditions. However, the placement of rock phosphate (low soluble P) resulted in lower P uptake compared to the broadcast application. In summary, the results of the studies by Bornø et al. (2023), Lemming et al. (2016) and Rosendo dos Santos et al. (2018) indicate that for low soluble P fertilizers, the placement may reduce the contact area with the soil, reducing the reactivity and dissolution of recalcitrant P forms over time. Thus, for fertilizer materials with low or near-zero P solubility, the reduced fertilizer contact area with the soil—previously mentioned as an advantage of mineral P fertilizers—may actually have a negative effect, reducing P availability.

4.1.2 | Biobased fertilizers with low P solubility

In Table 2, we highlight that biobased fertilizers with low P solubility, such as sewage sludge (1.2%–2.3%) and digestate solid fraction (~14%), can attract root growth to the placement zone. As shown in Figure 3, sewage sludge attracted root growth and proliferation in the placement zone (a). This proliferation was also visible for pea roots in

TABLE 2 Description of mineral fertilizers and biowastes from various studies that were applied localized as P fertilizers and showed no effect or attracted root growth of different crops to the placement zone.

	Total P	WEP	Total N	Total applied*				
Fertilizer	**$g\,kg^{-1}$**	**% of total P**	**$g\,kg^{-1}$**	**N (mg)**	**P (mg)**	**Application method**	**Soil type**	**Crop**
No root response								
Sewage sludge ash[a]	104	0.03	n.d.	n.d.	96	Placed, 5 cm depth in 2.4 kg rhizoboxes	Sandy loam, luvisol	Maize
Sewage sludge biochar[b]	70	0.03	n.d.	n.d.	154	Placed, 5 cm depth in 2.4 kg rhizoboxes	Sandy loam, luvisol	Wheat
Increased root proliferation in the placement zone								
Sewage sludge[a]	33	1.2	47	133	96	Placed, 5 cm depth in 2.4 kg rhizoboxes	Sandy loam, luvisol	Maize
TSP[a]	180	63	n.d.	n.d.	96			
Sewage sludge[b]	40	2.3	n.d.	n.d.	21.6	Placed, 5 cm depth in 2.4 kg rhizoboxes	Sandy loam, luvisol	Wheat
TSP + ammonium sulfate[c]	208	N.I.	N.I.	46	100	Placed, 25 cm depth in rhizoboxes	Vertisol	Sorghum
MAP[c]	219	N.I.	100	46	100			
MAP[d]	219	N.I.	100	207	455	Placed, 30 cm depth in rhizoboxes	Vertisol	Wheat and Sorghum
				20	44	Placed, 3 cm depth in rhizoboxes	Vertisol	
Sewage sludge[e]	34	0.6	29	102	120	Placed, 5 cm depth 2 kg in rhizoboxes	Sandy loam, luvisol	Wheat
Digestate solid fraction[e]	33	14	27	98	120			

[a]Lemming et al. (2016).

[b]Bornø et al. (2023).

[c]van der Bom, Williams, Raymond, et al. (2023).

[d]van der Bom, Williams, Borrell, et al. (2023).

[e]Figure 3. n.d. non detected or virtually zero; N.I. information not given by the authors.

*Total amount of P and N applied were calculated based on information provided by the authors.

TABLE 3 Description of mineral fertilizers and biobased fertilizers that were placed in the soil in different studies and caused ammonium toxicity in different crops, inhibiting root and/or plant growth.

	Total P	WEP	Total N	Total applied**		$N\text{-}NH_4^+$			
Fertilizer	$g\,kg^{-1}$	% of total P	$g\,kg^{-1}$	N (mg)	P (mg)	$mg\,kg^{-1}$***	Application method	Soil type	Crop
Sewage sludge + ammonium chloride[a]	34	N.I.	44	204	96	35	Placed, 5 cm depth, 2.4 kg in rhizoboxes	Sandy loam, luvisol	Wheat
Chicken manure[b]	N.I.	N.I.	N.I.	N.I.	N.I.	486 in the zone and 718 above	Layer at 11 cm depth, in rhizoboxes	Silt loam	Faba bean
Mature compost[b]	N.I.	N.I.	N.I.	N.I.	N.I.	117 in the layer and 7 above it			
Meat and bone meal[c]	39.6	0.89	99	300	120	400-600	Placed, 5 cm depth, in 2 kg rhizoboxes	Sandy loam, luvisol	Wheat
Cattle slurry[d]	0.04%*	N.I.	0.06%*	741	111	50-250	Band 1.5, 5, 8.5 and 12 cm below the seed in 3.9 kg pots	Coarse sand	Maize
Cattle slurry[e]	0.03%*	N.I.	0.06%*	300	56	n.d.	Band 2, 5 and 8 cm depth, in 3.9 kg pots	Loamy and coarse sand	Maize
		N.I.				n.d.	Layer 5 cm depth, in 3.9 kg pots		

[a]Wang et al. (2016).
[b]Pan et al. (2016).
[c]Figure 3.
[d]Pedersen et al. (2020).
[e]Baral et al. (2021). n.d. non detected or virtually zero; N.I. information not given by the authors.
*Values for cattle slurry for P and N are represented in percentage of fresh weight. **Total amount of P and N applied were calculated based on information provided by the authors. ***ammonium contents in the soil next to the placement zone.

the placement zone of the digestate solid fraction and its surrounding soil (b).

The results of Bornø et al. (2023) demonstrated that the placement zone of sewage sludge creates a 'hot-spot' in the soil with high alkaline and acid phosphatase activity. It also creates a 'hot-spot' for root proliferation with higher labile P. Thus, the sewage sludge may have enough soluble P to attract root growth. However, it did not provide enough P to sustain plant growth (Lemming et al., 2016), as explained below.

Lemming et al. (2016) observed a significant increase in root proliferation in the placement zone. However, using the indirect ^{33}P labeling method, they found that the placement reduced total P uptake, primarily by reducing P uptake from the soil. Thus, by concentrating root proliferation in the placement zone, the plants had less access to the main body of the soil. Based on these results, the authors suggested that the placement of biobased fertilizers entailed an opportunity cost for the plant. Other studies have confirmed that a labile P-rich zone may cause the plant to preferentially allocate its growing resources (carbon) into the placement zone (Lynch et al., 2005; Lynch & Ho, 2005), potentially reducing the exploration of other resources in the bulk soil (Ho et al., 2005). This is exacerbated when using low-soluble P biobased fertilizers, as these materials have enough soluble P to attract root growth; however, it is not sufficient to sustain plant growth in the early stages. Thus, it is not as effective as a starter fertilizer as highly soluble mineral P sources.

Considering the experimental design of Lemming et al. (2016), briefly described in Table 2, they applied 96 mg of total P with sewage sludge. Only 1.2% of this (1.15 mg) was soluble in water. At the end of the experiment, maize plants from this treatment had about 0.87 g of total shoot dry matter, with a total P uptake of 1.26 mg. Of this, 0.6 mg came from the fertilizer, 0.2 from the soil and 0.46 from the seed. For the sewage sludge mixed with the soil, the total P uptake was significantly higher with 1.67 mg. Almost no differences were observed in P derived from fertilizer (~0.6 mg) and seeds (0.5 mg). However, soil-derived P was about two times higher in the mixed treatment. In fact, in this same study, Lemming et al. (2016) placed 96 mg of total P as triple superphosphate (~70% of total water-soluble P, ~67 mg soluble P). In this treatment, shoot dry matter was 1.94 g and total P uptake was 3.43 mg per plant. Thus, the lower P solubility may be a

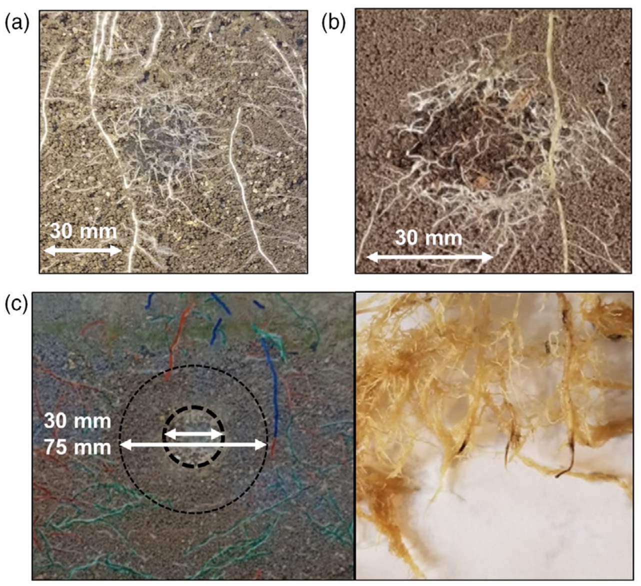


FIGURE 3 Pictures showing the response of wheat roots to the placement of sewage sludge (a), pea roots to the placement of digestate solid fraction (b), and wheat roots to the placement of meat and bone meal (inner circle) with high ammonium content zone (outer circle) and damaged roots (c).
Source: Authors.

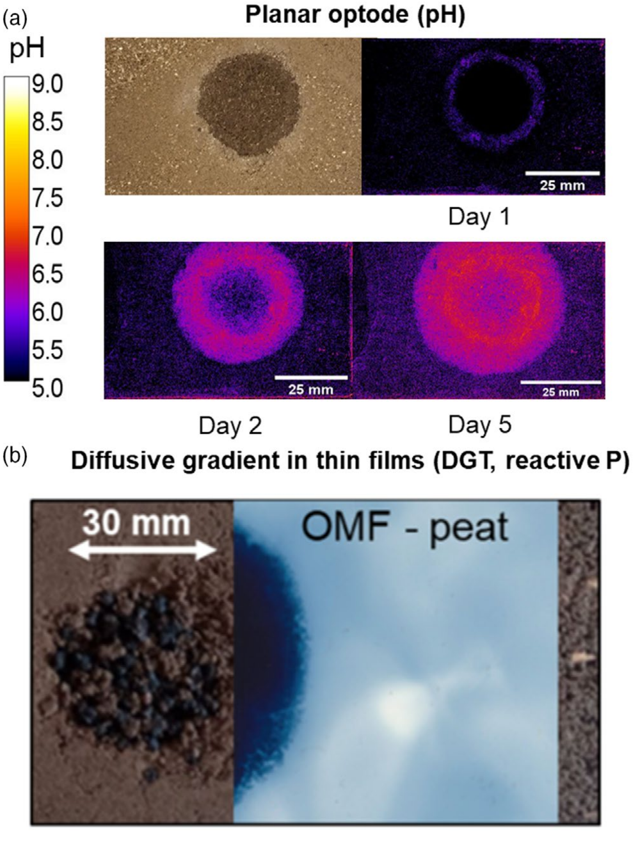


FIGURE 4 Planar optode images showing pH variation in the placement zone and surrounding soil of acidified digestate solid fraction (a) and phosphorus diffusion in the soil surrounding the placement zone of an organo-mineral fertilizer with peat as the organic matrix (Sitzmann et al., 2024) (b). The more intense the blue colour, the higher the reactive P concentration.
Source: Authors.

factor limiting the potential benefits of biobased fertilizer placement compared to mineral P fertilizers.

4.2 | Ammonium toxicity

As discussed in the previous subsection, the placement of sewage sludge attracts root growth to the placement zone (Bornø et al., 2023; Lemming et al., 2016). Wang et al. (2016) co-applied sewage sludge with ammonium chloride (total N: 204 mg kg soil^{-1}; total P: 96 mg kg soil^{-1}) in the placement zone near wheat seeds (Table 2). Co-application of ammonium chloride significantly reduced root length density in the placement zone and reduced shoot dry matter and P uptake compared to the placement of sewage sludge. The authors attributed this to ammonium toxicity in the placement zone. Therefore, a slight increase in ammonium levels in the placement zone can be detrimental to root growth.

The unbalanced N:P ratio of biobased fertilizers (Prado et al., 2022) is also a factor that may have negative effects when they are applied placed in the soil. As shown in Table 3, in cases where root proliferation was increased in the placement zone, the total P applied was higher than the total N applied (in the case of mineral fertilizers (van der Bom, Williams, Borrell, et al., 2023; van der Bom, Williams, Raymond, et al., 2023)) or similar (in the case of sewage sludge (Bornø et al., 2023; Lemming et al., 2016; Wang et al., 2016)). However, in the case of animal-derived residues, such as pig slurry, cattle manure, poultry litter and meat and bone meal, the total N contents were considerably higher than the total P content (2–5 times) (Tables 1 and 3).

The N in these materials is mainly in organic form and can be rapidly mineralized after application to the soil (Chaves et al., 2006). The mineralization will release high amounts of ammonium (NH_4^+) into the placement zone and the surrounding soil. Elevated ammonium contents may create a toxicity zone, damaging the roots and negatively affecting plant growth (Baral et al., 2021; Makaza & Khiari, 2023; Pan et al., 2016; Pedersen et al., 2017, 2020), as ammonium can be toxic to the plant at levels above 100 mg kg^{-1} (Nkebiwe et al., 2017).

Figure 3c illustrates how ammonium toxicity can affect root growth around the placement zone of meat and bone meal. Notably, the placement zone has a diameter of 30 mm, while the ammonium toxicity zone extends to greater distances, creating a root-free zone with a diameter of 75 mm. In this study, the ammonium content in the toxicity zone ranged from 400 to 600 mg kg soil^{-1} (unpublished data). Pan et al. (2016) also observed root growth inhibition and reduced plant growth with the placement of chicken manure and composted manure. The chicken manure increased the N-$NH4^+$ contents in the placement zone and its surrounding soil to more than 400 mg kg^{-1}. For the composted manure, these values were around 100 mg kg^{-}1. Ammonium toxicity and root damage were also observed with the injection of cattle manure in studies by Pedersen et al. (2017, 2020).

In Figure 1c, it can be seen that the roots in direct contact with the surroundings of the toxicity zone had burned tips. Browning and subsequent burning of root tips in areas of high soil ammonium concentrations are typical symptoms of toxicity (Britto & Kronzucker, 2002; Hoque et al., 2008). Elevated ammonium contents affect cell elongation and division, leading to cell death over time. This process starts in the maturation and elongation zones and spreads through the meristem and root cap cells (Qin et al., 2011). It is known that ammonium toxicity has other negative side effects that stress the plants and inhibit growth. These effects include 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). These effects may reduce root development, nutrient acquisition and plant growth (Baral et al., 2021; Makaza & Khiari, 2023; Pedersen et al., 2017, 2020).

It should be noted, however, that the examples of ammonium toxicity cited in this review are mainly from rhizobox and pot experiments. We suggest that this experimental design confines the soil to smaller volumes, which may exacerbate this negative effect. Therefore, ammonium toxicity from biobased fertilizer could be alleviated under field conditions. Furthermore, the main symptom is root damage, which has been reported (Hunter & Rosenau, 1966; Makaza & Khiari, 2023) but is more difficult to observe and study under field conditions (Britto & Kronzucker, 2002; Esteban et al., 2016).

4.3 | Soil microbial activity and P turnover

The placement of P-rich biobased fertilizers also supplies other nutrients, such as nitrogen and organic matter, which can influence soil microbial activity and, consequently, P turnover. This effect depends largely on the material's composition. For instance, Sica, Kopp, Magid, and Müller-Stöver (2023) observed an increase in microbial growth both in the placement zone and surrounding soil just days after applying meat and bone meal. This fertilizer had a low C:N ratio (4.4) and contained organic matter rich in labile carbon compounds (Jeng et al., 2007). In contrast, no such microbial response was observed with the digestate solid fraction, which has a higher C:N ratio (15.9) and contains more recalcitrant carbon forms (Chuda & Ziemin'ski, 2021).

It is well established that the addition of different elements influences soil microbial biomass C:N:P stoichiometry, which in turn affects P turnover (Chen et al., 2019). According to Heuck et al. (2015), changes in C:N:P ratios primarily impact soil organic P mineralization when microorganisms require carbon. On the other hand, the addition of carbon and nitrogen may increase the P immobilization by the soil microbial community (Sica et al., 2025). Additionally, soil organic P mineralization may depend on the availability of labile P. As noted by Pistocchi et al. (2018), in soils with low P availability microbial immobilization represents the main P flux, with labile P being rapidly cycled biologically following the addition of other elements alongside phosphorus.

Sica et al. (2025) used the ^{18}O isotope as a tracer to investigate soil biotic effects on P dynamics following the placement of acidified meat and bone meal and digestate solid fraction in a two-week incubation experiment. Their findings showed that untreated meat and bone meal significantly increased microbial respiration and ^{18}O-P incorporation into microbial biomass, facilitating P transport from the placement zone through the soil. They also observed a strong correlation between microbial respiration and ^{18}O-P incorporation into microbial biomass, consistent with the findings of Siegenthaler et al. (2020).

Sica et al. (2025) concluded that the placement of biobased fertilizers can influence P turnover in soils and promote P immobilization. However, they emphasized that the incorporation of labile P into the microbial community occurred within just 2 weeks. Over longer periods, shifts in C:N:P stoichiometry may alter microbial communities, affecting P mineralization and subsequent release into the soil.

5 | STRATEGIES TO IMPROVE BIOBASED FERTILIZERS PLACEMENT EFFICIENCY

5.1 | Increasing P solubility

Sica, Kopp, Magid, and Müller-Stöver (2023) suggested that for more efficient placement of biowaste, pretreatments would be needed to increase their P solubility, so that a greater amount of P would be available to the crop in the application zone during early growth stages. They found that acidification with sulfuric acid of meat and bone meal, sewage sludge, sewage sludge ash and the solid fraction of digestate significantly increased the water-extractable P in these materials. When the acidified materials were applied to the soil, it was also observed that they significantly increased the release of P from the fertilizer to the soil and the recovery of water-extractable P in the soil surrounding the application zone compared to the untreated materials. For sewage sludge and sewage sludge ash, the study found that alkalinization with sodium hydroxide did not increase water-soluble P and P release to soil to the same extent as acidification. However, the water-soluble P recovered in the soil for this treatment was significantly higher than for the corresponding acidified treatments. Sica, Kopp, Magid, and Müller-Stöver (2023) concluded that the acidification pretreatment of all materials and the alkalinization with sodium hydroxide of sewage sludge and sewage sludge ash are promising approaches to increase the P use efficiency of biowastes placed in the soil, taking a step forward in the formulation of efficient P-rich biobased fertilizers.

In another study, Pedersen et al. (2017) conducted experiments involving the application of both raw and acidified cattle slurry. The application was carried out in two different ways: as a full layer and as a banded layer (stripe) near the seed in two different soil types. The researchers found that the banded application of acidified cattle manure significantly increased the P uptake and early growth of corn. The results suggest that band injection of acidified cattle manure holds promise as an effective starter fertilizer for corn production, demonstrating its potential to positively impact the early stages of plant development and nutrient assimilation.

Regueiro et al. (2020) demonstrated that placing the acidified slurry solid fraction significantly increased shoot biomass and P uptake compared to untreated material. They also found a significant increase in P uptake when comparing the placed acidified digestate solid fraction with the untreated digestate solid fraction. In the study by Sica, Kopp, Müller-Stöver, and Magid (2023), results showed that the placement of acidified digestate solid fraction doubled the total P uptake by wheat compared to the mixed application of untreated material. Moreover, using ^{33}P radioisotopes, the authors found that the P derived from the fertilizer increased threefold when combining placement and acidification and were even higher than the mineral fertilizer they used as a reference. In both studies, the researchers concluded that placing acidified slurry and digestate solid fractions could be promising starter fertilizers to replace mineral fertilizers.

It should be noted, however, that the success of placement and acidification depends on the composition of the biowaste. Kopp, Sica, Magid, and Muller-Stover (2023) acidified various sewage sludges and applied them mixed with soil and found a significant increase in P availability and maize growth. Keskinen et al. (2023) also demonstrated the potential of acidification to increase the P solubility when mixed with the soil. However, Keskinen et al. (2023) pointed out that the acidification may also solubilize harmful metals, especially from sewage sludge. Indeed, Sica, Kopp, Müller-Stöver, and Magid (2023) and Kopp, Sica, Magid, and Muller-Stover (2023) found that the placement of acidified sewage sludge inhibited plant growth and reduced P uptake. They suggested that this may be due to the increased solubilization of metals such as aluminium when high concentrations are applied in the placement zone, which is toxic to roots and plant growth (Imadi et al., 2016; Roy et al., 1988).

5.2 | Strategies to alleviate the ammonium toxicity

Westerschulte et al. (2015, 2016, 2018) and Federolf et al. (2016, 2017) injected raw slurry 10 cm below the soil surface 1 week before sowing. Although not explicitly mentioned by the authors, we suggest that placing the fertilizer more than five centimetres away from the seeds and before sowing would likely mitigate the effects of ammonium toxicity. Moreover, Federolf et al. (2016) and Westerschulte et al. (2016) found that the ammonium content in the application zone and surrounding soil of injected animal slurry tended to decrease over time, indicating that the effects of ammonium toxicity could be mitigated if N-rich biobased fertilizers were placed before sowing.

Pedersen et al. (2020) suggested placing the animal-derived slurry a few centimetres from the seeds as a strategy to alleviate damage on roots at early stages, as ammonium contents are lower at these distances and tend to decrease over time. Delin et al. (2018) investigated the nitrogen fertilizer efficiency of placing meat and bone meal at various distances from the seed row. They found that efficiency increased with increasing distance from the seeds. Therefore, they recommended the placement of meat and bone meal 5 cm on the side of the seed row under field conditions to increase N use efficiency. Therefore, the timing of fertilizer application and the distance from the seed row may mitigate potential ammonium toxicity in the placement zone (Makaza & Khiari, 2023).

Results from Sica, Kopp, Müller-Stöver, and Magid (2023) indicated that the acidification of meat and bone meal mitigated the effects of ammonium toxicity when placed in the soil. Using ^{33}P radioisotopes, they showed that the placement of untreated meat and bone meal significantly reduced wheat growth, with virtually no P uptake from the fertilizer. In contrast, the placement of acidified meat and bone meal considerably increased both the total P uptake and the P derived from the fertilizer, resulting in a significant increase in plant growth 42 days after sowing. The authors found that because ammonium toxicity created a root-free area around the placement zone (as shown in Figure 3c) and most of the labile P remained within the placement zone, the roots did not have access to the P from the fertilizer. However, acidification increased P diffusion to greater distances than the root-free zone, providing P from the fertilizer to the roots around the toxicity zone.

In the case of liquid fertilizers, such as animal slurry and digestate, the separation of the liquid and solid fraction is a simple and relatively inexpensive method that can improve the management, distribution and field application of N and P (Chuda & Ziemin'ski, 2021). The fraction separation also allows a field application aiming to meet the crop demands and avoid overapplication. The solid fraction will have a relatively high P content, which can be acidified and placed as an efficient starter fertilizer, as previously discussed based on Regueiro et al. (2020). The liquid fraction will recover a considerable part of the N, which can be applied according to the crop demand, reducing the risk of ammonium toxicity (Tambone et al., 2017).

6 | METHODOLOGIES TO ASSESS PLACEMENT ZONE OF P FERTILIZERS

For a better understanding of the effects of the placement of mineral and biobased fertilizers, it is essential to assess the nutrient dynamics in the nutrient-rich zone, taking into account the physical, chemical and biological interactions that determine the availability of P and the potential toxicity of harmful elements. In this section, we describe different techniques to assess these interactions.

6.1 | Example of field sampling strategies

The fertilizer placement under field conditions should use the seed row as the reference zone during fertilizer application, as shown in Figure 1. This reference should also guide soil sampling in field experiments (Drazic et al., 2020; Makaza & Khiari, 2023). To assess nitrogen dynamics after slurry injection in the subsurface of the maize seed row (12 cm depth), Westerschulte et al. (2015) proposed a soil sampling strategy aimed at assessing N mineralization in the application zone and surrounding soil. The sampling was performed using a custom-built soil metal spade measuring 15 cm wide, 15 cm high and 10 cm deep, which allowed the researchers to collect soil monoliths at different depths, including one that covered the entire placement zone, and to measure the ammonium content in the placement zone and surrounding soil over time. They demonstrated that this sampling strategy was more reliable than simply drilling an auger through the slurry band and that adjacent soil should be avoided. Westerschulte et al. (2016) used the same spade to collect soil monoliths in the topsoil (15 cm wide × 30 cm deep) and collected soil samples with an auger at 15 and 30 cm from the seed row at 0–30, 30–60 and 60–90 cm depths. They analysed the ammonium content at different distances and depths from the placement zone over time to assess the effects of a nitrification inhibitor on N dynamics from pig slurry in the soil at different sampling times. They demonstrated a consistent decrease in soil inorganic N over time and at greater distances and depths from the injection row.

In another study, Westerschulte et al. (2018) also assessed root interaction with pig slurry placed 12 cm below the soil surface. To improve the clarity of the placement zone and visualize root interaction with the slurry, they stained the slurry with brilliant blue food colouring (E133). They observed that 66 days after planting (73 days after applying the slurry), maize roots were proliferating in the placement zone. This proliferation may have improved the plant's ability to acquire nutrients, such as phosphorus, zinc and manganese from the fertilizer.

de Oliveira et al. (2022) applied triple superphosphate and rock phosphate placed 5 cm from the soil surface and by broadcasting. They collected soil samples from the seed row (placement zone), and at 12.5, 25 and 37.5 cm from the seed row (on both sides of the row) and for each sample, they assessed four depths (0–5, 5–10, 10–20 and 20–30 cm), giving a total of 28 soil subsamples per sampling. They measured total P and labile P (Mehlich-1 method) in each subsample. They performed a 2-D geostatistical analyses in R, by estimating non-sampled areas by means of ordinary kriging. That allowed the authors to create a two-dimensional distribution of P in the soil and compare the effects of placement and broadcast on P dynamics over time.

6.2 | Incubation experiments (soil-fertilizer)

Incubation experiments are used to assess the interactions between soils and fertilizers. Different setups can be used, depending on the aim of the study, to provide valuable insights into the mechanisms that drive phosphorus dynamics in the soils.

A common setup involves the use of Petri dishes filled with soil. The fertilizer is placed in the centre of the petri dish, which is then sealed and incubated under controlled temperature conditions for a specified period of time. Soil samples can be collected at different distances from the placement zone using concentric discs of varying diameters. For example, Lombi et al. (2005) used this setup and collected soil samples at distances such as 0–7.5, 7.5–13.5, 13.5–25.5 and 25.5–43 mm from the placement zone. This configuration allows the assessment of phosphorus mobility, solubility, availability (Lombi et al., 2004, 2005), speciation and distribution in the soil surrounding the placement zone (Lombi et al., 2006).

Degryse and McLaughlin (2014) used the same setup in Petri dishes. They investigated the two-dimensional spatiotemporal diffusion of phosphorus from the fertilizer through different soils. After incubation, they applied a Fe-oxide-enriched paper for 5 min for shorter incubation periods and 30 min for longer ones. The principle of this method is to trap diffusible phosphorus on the iron oxides (Chardon et al., 1996). After application, they used the ammonium molybdate malachite green reagent to produce colour, with the colour indicating phosphorus diffusion in the soils. In another study, Degryse et al. (2017) used the same protocol to assess the dissolution rate and diffusion of different struvites compared to monoammonium phosphate. The same setup can be used with Diffusive Gradient in Thin Films (DGT) gels of zirconium oxide and using the molybdate blue method for colour formation (Bornø et al., 2023).

Another setup used to assess concentrated bands involves the application of fertilizers at high rates. For example, in incubation experiments, the fertilizer is applied at very low rates, such as 50 mg of total P per kg of soil (Lemming et al., 2017). Meyer et al. (2020, 2021) applied 8200 mg of total P in incubation experiments, aiming to simulate highly concentrated P bands in the soil at an application rate of 40 kg of total P per hectare. In both studies, they assessed P availability (Meyer et al., 2020) and speciation using synchrotron-based X-ray absorption near-edge structure spectroscopy (XANES) at the K-edge (Meyer et al., 2021) after applying different P sources to different soils.

One-dimensional reaction systems can also be used to assess the P dynamics in concentrated soil patches. Rech et al. (2018) placed struvite and triple superphosphate on the soil surface in PVC soil columns, 28 mm in diameter and 50 mm long. After incubation, they used a microtome to slice the soil every 1 mm and assessed the P diffusion from the application zone. A microtome is a specialized precision cut instrument, able to slice different materials (including soils) in thin layers (up to 20 μm precision). Sica, Kopp, Magid, and Müller-Stöver (2023) used a one-dimensional reaction system, consisting of the incubation of a fertilizer layer (2 mm) between two soil columns (60 mm diameter × 17 mm depth). They placed a 0.45 μm nylon mesh between the fertilizer and the soil. After incubation, the soil columns were sliced into 1 mm layers using a specially designed slicing piston and P diffusion rates were estimated. With this setup, they were also able to collect and analyse the fertilizer (between the nylon meshes) after the incubation. In a similar approach, Pedersen et al. (2020) performed an incubation in large soil columns (10.3 cm diameter × 27.5 cm height) and used a hydraulic pusher to move the soil upwards and a knife to cut the soil column into 5 mm layers.

6.3 | Controlled plant trials (soil-fertilizer-roots)

Plant trials under controlled conditions can provide relevant information on soil–plant–fertilizer interactions. Most plant trials aim to assess the P availability (or mineral fertilizer equivalent) of biobased fertilizers and do not directly compare different application methods (Bogdan et al., 2023; Brod, Øgaard, Hansen, et al., 2015; Brod, Øgaard, Haraldsen, & Krogstad, 2015; Christiansen et al., 2020; Ylivainio et al., 2021). However, as shown in Figure 1, even within a pot or rhizobox setup, different fertilizer application methods can be used, potentially influencing the results obtained and the interpretation of the data.

Authors often interpret their results without considering the ammonium toxicity as a relevant factor. For example, Christiansen et al. (2020) placed meat and bone meal in a full layer and observed low P uptake. They attributed these results to the soil pH. According to Brod, Øgaard, Hansen, et al. (2015), the soil pH has a strong effect on P availability of meat and bone meal, which is favoured at lower pH. However, Christiansen et al. (2020) used soils with relatively low pH (5.2) and still found low P availability. As can be seen in Figure 3, the application of 300 mg of meat and bone meal resulted in a toxicity zone of 7.5 cm. Based on the information provided by the authors, we estimated that Christiansen et al. (2020) applied 687 mg N from meat and bone meal in a concentrated band. As can be seen in Table 3, localized application of more than 200 mg of total N (from organic sources or ammonium salt), have been found to cause ammonium toxicity. Sica, Kopp, Magid, and Müller-Stöver (2023) showed that meat and bone meal P diffused only a few millimetres from the placement zone. Therefore, we speculate that in the study by Christiansen et al. (2020), an ammonium toxicity zone was formed, inhibiting root growth and preventing it from accessing P from the meat and bone meal.

Rhizoboxes are also an important tool to assess the effect of different fertilization strategies on plant growth, root architecture and nutrient acquisition. As shown in Figure 3, the fertilizer composition will strongly affect the root growth pattern, which in turn will affect the nutrient acquisition and plant growth (Lemming et al., 2016; Pan et al., 2016; van der Bom, Williams, Borrell, et al., 2023; van der Bom, Williams, Raymond, et al., 2023; Wang et al., 2016).

6.4 | Novel visualization techniques

The placement zone creates a nutrient-rich patch in the soil, with intensified physical, chemical and biological processes that will interact and affect each other and the nutrient availability. Recently developed advanced techniques with high spatial and temporal resolution will elucidate how biogeochemical interactions affect N and P dynamics in the fertosphere over time (van der Bom et al., 2022). Bornø et al. (2023) placed sewage sludge and sewage sludge biochar close to the seeds and used: planar optodes, zymography and diffusive gradient in thin films (DGT) gels to assess biogeochemical interactions in the placement zone.

Optodes are non-invasive sensors that can be deployed in the soil to monitor analyte concentration changes over time (hours, days, or weeks) (Merl & Koren, 2020; Santner et al., 2015). The principle of planar optodes in soil measurements is based on the luminescence intensity of an analyte-specific sensor foil (planar optode). Images are captured by a digital single-lens reflex camera with a filter specific for the desired analyses (e.g. for pH: yellow 455 nm long-pass filter) and a filter for the excitation of the fluorescence (e.g. for pH: UV LED, 405 nm). The images can be analysed as RGB and colour and the desired parameter variation can be determined based on a calibration curve (Bornø et al., 2023; Christel et al., 2016). Planar optodes can also be used for two-dimensional imaging of other elements, such as O_2, NH_3, H_2S (Li et al., 2019; Merl et al., 2023; Merl & Koren, 2020). An example of the use of planar optodes is shown in Figure 4a. The images show how the pH in the placement zone of acidified digestate solid fraction changes over a 5-day period and how its effect in the soil increases over time.

The use of visualization techniques to map the dynamics of reactive P (or labile P) in the soil has already been briefly discussed in this review (Degryse et al., 2017;

Degryse & McLaughlin, 2014). It involves the use of a sink (e.g. iron oxide-enriched paper or Diffusive Gradients in Thin Films) that is placed on the soil surface and captures the reactive (or labile) P (van der Bom et al., 2022). The captured P gradients in the soil can be mapped by using different techniques, such as colorimetry, scanning electron microscopy (SEM) and laser ablation ICP-MS (LA-ICP-MS).

The technique using iron oxide-enriched papers can be coupled with colorimetric methods, as the ammonium molybdate malachite green reagent (Degryse et al., 2017; Degryse & McLaughlin, 2014). Li and Erel (2020) also used iron oxide-enriched paper and generated a high-resolution map of labile P using scanning electron microscopy, equipped with energy dispersive X-ray spectroscopy (SEM-EDS). They found that the P extracted from the iron oxide papers was highly correlated with Olsen-P (R^2: .99).

The Diffusive Gradient in Thin Films (DGT) device consists of a filter membrane in direct contact with the soil surface, a diffusive layer, and a binding layer (Santner et al., 2010). The binding layer contains a specific binding agent that, in the case of phosphorus, can be iron-based (Santner et al., 2010) or, more recently and increasingly popular, zirconium oxide (Zr_2O) (Ding et al., 2013) due to its greater ability to bind P (van der Bom et al., 2022). After deploying and incubating the DGT gels in the placement zone of raw sewage sludge and its biochar for 24 h, Bornø et al. (2023) used ammonium molybdate solution to form colour (blue) and scanned the images. An example of a scanned image after colour forming with ammonium molybdate is shown in Figure 4b. This image shows the P movement from the placement zone of an organo-mineral fertilizer (10% N, 2.25% P) with peat as the organic matrix (7.5% organic carbon) through the soil after 7 days of incubation in a rhixobox setup. In this case, the gel incubation time was only 3 h, shorter than in Bornø et al. (2023), because a highly soluble P fertilizer was used and the higher labile P concentrations saturated the gel at longer incubation periods.

The incubation time of the gel on the surface is a relevant piece of information to produce a gradient map. Bornø et al. (2023) created a calibration curve (ranging from 0 to 1500 μg P L^{-1} solutions, with small pieces of the gel) and processed it with the scanned images using the software ImageJ. The grayscale values were then plotted against the calculated P fluxes (pg P $cm^{-2} s^{-1}$), representing the average time of P flux towards the DGT gel over a given area during the deployment period. This information was used to produce maps showing the intensity and gradient of P fluxes in the placement zone and the surrounding soil.

The Diffusive Gradients in Thin Films can also be used for the simultaneous mapping of cations and anions. The principle is the same as described above. However, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) can be used to image the gradients in the gel. Kreuzeder et al. (2013) used this technique by deploying a zirconium-hydroxide DGT gel in the rhizosphere of maize for 24 h and mapped phosphorus, manganese, copper, arsenic and zinc in the soil surrounding the roots.

7 | RHIZOBOX TRIAL WITH DGT: A DESCRIPTIVE EXAMPLE

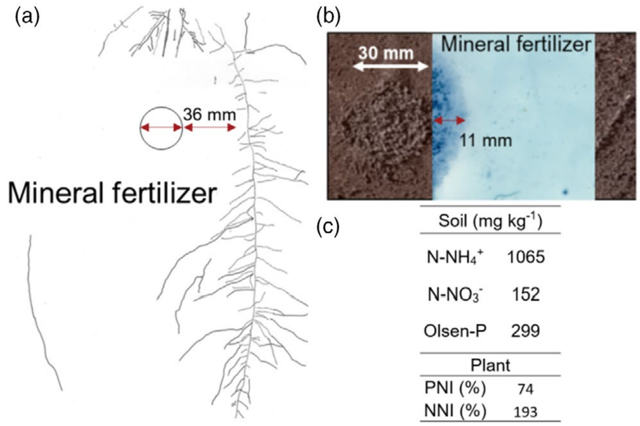
The objective of this experiment was to demonstrate how the co-placement of N and P can cause ammonium toxicity to the crop, inhibiting root growth and reducing P uptake from the placement zone.

7.1 | Brief description of the experimental design

The soil used in this study was collected from an unfertilized plot (CRUCIAL long-term trial) since 2003, air dried and sieved to 2 mm (for more information see (Sica, Kopp, Magid, & Müller-Stöver, 2023)). Nutrient solutions were added to provide all nutrients except nitrogen and phosphorus. A mineral fertilizer consisting of ammonium sulfate, urea (10% total nitrogen) and triple superphosphate (2.1% total P) was placed 8-cm below the seeds at a rate of 300 mg of N and 63 mg of P kg $soil^{-1}$. Maize was grown for 30 days under controlled conditions. At the end of the experiment, soil samples were taken next to the placement zone: N-NH_4^+, N-NO_3^- (1:5 KCl), and Olsen-P were measured. The plant nutrient indices were calculated according to Ziadi et al. (2008) (for nitrogen nutrient index, NNI) and Gagnon et al. (2020) (for phosphorus nutrient index, PNI). After 14 days, a DGT gel was deployed in the soil near the placement zone and then immersed in ammonium molybdate solution.

7.2 | Main findings

The main results of this experiment are shown in Figure 5. The co-placement of N and P in a 30 mm diameter placement zone, created a root-free zone that extended 36 mm away from it (Figure 5a). However, the DGT gel showed that the P diffusion from the placement zone was limited to 11 mm through the soil (Figure 5b).



	Soil (mg kg^{-1})
N-NH_4^+	1065
N-NO_3^-	152
Olsen-P	299
	Plant
PNI (%)	74
NNI (%)	193

FIGURE 5 Maize root growth pattern at 30 days after emergence in a rhizobox with N and P supplied as mineral fertilizer, placed in a 30-mm diameter circle at 8 cm below the seed. The root-free zone around the placement zone is indicated (a). The P diffusion from the placement zone into the soil is illustrated by the Diffusive Gradient in Thin Films colorimetric image (b). The soil ammonium, nitrate and Olsen-P and the plant phosphorus and nitrogen nutrient indices are shown in (c).

The soil collected from the root-free zone had very high ammonium (>1000 mg kg^{-1}) and Olsen-P contents (~300 mg kg^{-1}) (Figure 5c).

These results show that the ammonium toxicity zone (Figure 5a) extended over a larger area than the P diffused from the fertilizer (Figure 5b), which, in turn, limited the plant's access to the P. This is confirmed by the nutrient indices (Figure 5c). These values are calculated by dividing the actual nutrient content in the shoots by the critical nutrient content. Thus, 100% indicates a sufficient fertilization, whereas lower values (<80%) indicate a deficiency and higher values (>120%) indicate a luxurious uptake (Duru & Ducrocq, 1997).

The placement of mineral nitrogen fertilizer at high and toxic concentrations creates a significant nitrogen gradient to the bulk soil, and the elevated ammonium content inhibits microbial nitrification (Sommer & Scherer, 2009). This process is known as 'CULTAN' (controlled long-term ammonium nutrition) and can be applied to increase crop yield and nitrogen use efficiency (Kozlovský et al., 2009). The results of Nkebiwe et al. (2017) show that the overapplication of nitrogen creates a toxicity zone, similar to the one shown in Figure 5. They also show that at the edge of the toxicity zone, there is a high root proliferation, increased plant growth-promoting microorganisms, reduced pH, higher Ca-P solubilization, and increased phosphorus and nitrogen uptake. Regarding nitrogen, our results are in agreement with theirs, as the Nitrogen Nutrition Index (NNI) was almost 200%, indicating a luxurious nitrogen uptake by the crop. However, it is worth noting that Nkebiwe et al. (2017) applied phosphorus as calcium phosphate and mixed it with the soil. Then, the enhanced interactions between plants and microorganisms at the edge of the toxicity zone increased phosphorus availability. Therefore, in contrast to Nkebiwe et al. (2017), our results indicate that the co-application of nitrogen and phosphorus into a placement zone may inhibit root growth and access to the phosphorus from the fertilizers, as the ammonium toxicity zone expands faster than the P diffusion in the soil.

8 | CONCLUSIONS

In summary, this review highlights the multiple benefits associated with the placement of soluble phosphorus-rich mineral fertilizers, including reduced soil contact area, increased early-stage phosphorus availability, enhanced root growth, increased yields, and a competitive advantage over weeds. However, the success of this practice depends on several factors, including soil higher P-sorption capacity, lower labile P content, water-holding capacity, susceptibility to drought, cold temperatures, placement method, and the amount and solubility of P and other elements applied.

However, in contrast to the placement of mineral P fertilizers, the placement of biobased fertilizers tends to have a negative effect on the plant, mainly due to two factors: low or no P solubility and a relatively high N:P ratio, resulting in a high nitrogen application in a concentrated soil zone, which may cause ammonium toxicity to the roots. Pretreatment such as acidification, which increases phosphorus solubility, can overcome the first limitation. Placement of acidified material can also reduce the effects of ammonium toxicity. In this case, it is recommended to place the material at a certain distance from the seed (>5 cm) to reduce the effects of toxicity on seedlings in the early stages. We also highlight that the combination of rhizobox experiments with newly developed visualization techniques such as planar optodes and Diffusive Gradient in Thin Films (DGT) gels in colorimetric imaging are methodologies that can elucidate spatiotemporal physical, chemical and biological processes in the placement zone and surrounding soil, providing insights for a better understanding of nutrient availability and improving the efficiency of placement of biobased fertilizers.

In conclusion, optimizing the placement of biobased fertilizers through a better understanding of their composition and placement strategy is key to unlocking their full fertilizer value potential. This not only contributes to sustainable agricultural practices, but also underlines the importance of considering multiple factors in fertilizer management strategies to improve agricultural productivity.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 860127 and from the Independent Research Fund Denmark, under the project PROCESSOR (Phosphorus Recycling frOm Complex scarcEly Soluble Societal resources—letting the sOil do the work), grant number 1032-00011B.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Pietro Sica https://orcid.org/0000-0002-2606-6361
Dorette Müller-Stöver https://orcid.org/0000-0001-7921-4471

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How to cite this article: Sica, P., Sitzmann, T. J., Müller-Stöver, D., & Magid, J. (2025). Strategic placement of mineral and biobased fertilizers for optimizing phosphorus use efficiency: A comprehensive review. *Soil Use and Management*, *41*, e70039. https://doi.org/10.1111/sum.70039