

Systematic Review

Phosphorus Use Efficiency and Soil–Plant Responses to Organomineral Phosphate Fertilizers in Maize and Bean Crops: A Systematic Review

Caroline Figueiredo Oliveira Selleri ¹, Camile Figueiredo Oliveira ², Luís Reynaldo Ferracciú Alleoni ³,
Vinícius de Melo Benites ⁴ and Elcio Ferreira Santos ^{1,2,*}

¹ Faculty of Agricultural Sciences, Federal University of Grande Dourados, Dourados 79804-970, MS, Brazil; caroline.oliveira059@academico.ufgd.edu.br

² Nova Andradina Campus, Federal Institute of Mato Grosso do Sul, Nova Andradina 79750-000, MS, Brazil; camile.oliveira@estudante.ifms.edu.br

³ Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba 13418-900, SP, Brazil; alleoni@usp.br

⁴ Embrapa Soils, Rio de Janeiro 22460-000, RJ, Brazil; vinicius.benites@embrapa.br

* Correspondence: elcio.santos@ifms.edu.br

Abstract

Phosphorus (P) is one of the most important nutrients to plants, but its bioavailability in agricultural soils is often limited by its low mobility and strong fixation in soil colloids, thus reducing crop productivity and phosphorus use efficiency (PUE). Organomineral fertilizers (OMFs) have been proposed as an alternative to increase the agronomic efficiency of P and promote sustainable soil–plant interactions. In this systematic review, we synthesized scientific evidence on the effects of OMFs on PUE, plant physiological responses, and soil attributes in maize and bean crops. The review followed PRISMA 2020 guidelines and included studies published between 2015 and 2025, retrieved from Scopus, Web of Science, ScienceDirect, SciELO, and Google Scholar. Selected studies compared organomineral phosphate fertilizers with conventional mineral sources and reported outcomes related to PUE, plant performance, or soil attributes. OMFs were generally associated with improved crop growth and increased soil P availability. However, despite frequent comparisons between OMFs and mineral fertilizers, few researchers quantitatively calculated PUE using robust metrics. Plant physiological responses were also poorly explored and, when assessed, were mainly restricted to chlorophyll indices. In addition, the soil microbiome was evaluated in only a few studies, highlighting a major gap in integrated soil–plant–microorganism research.

Keywords: plant physiology; soil attributes; nutrient utilization; recycling fertilizer; circular economy



Academic Editor: Chad J. Penn

Received: 25 May 2026

Revised: 27 June 2026

Accepted: 2 July 2026

Published: 7 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Phosphorus (P) is an essential element for plant growth and development, playing an important role in various metabolic and physiological processes, such as energy metabolism, cell division, DNA synthesis, and phospholipid formation [1–3]. Additionally, P regulates physiological responses that increase plant tolerance to abiotic stresses, such as heat, drought, salinity, flooding, heavy metal toxicity, and high CO₂ concentrations [4–6]. Understanding P dynamics in the soil and the mechanisms by which plants respond to its availability is fundamental for increasing phosphorus use efficiency (PUE).

In highly weathered tropical soils, PUE is challenging due to its strong fixation by minerals such as kaolinite, hematite, goethite, and gibbsite. This fixation reduces P availability to plants and requires frequent applications of phosphate fertilizers, which increases production costs and depletes finite and nonrenewable P resources [7]. In this context, organomineral fertilizers (OMFs) as a P source have been proposed as a promising alternative, as they combine mineral P sources with organic matrices. This association allows the production of fertilizers rich in soluble P, which can be efficiently used in large-scale agricultural systems [8–11].

Beyond providing nutrients, OMFs can alter P dynamics in the soil. Dissolved organic carbon in the organic matrix can compete for adsorption sites, which reduces P fixation and increases its mobility in the soil. Organic compounds, such as humic acids and plant residue extracts, can decrease P retention through competition with organic anions or by increasing the negative charge on soil surfaces, which inhibits nutrient adsorption [12–14]. However, the response to OMFs varies depending on the organic matrix used, the plant, the applied rate, and the management practices adopted [7,15].

Despite the increase in the number of studies on organomineral phosphate fertilizers, the results remain highly variable and, in some cases, contradictory regarding their effects on PUE and crop performance. Moreover, most researchers have focused on crop productivity indicators and soil chemical attributes, such as P availability, with little integration with plant physiological responses and the soil microbiome.

Evaluations that include the microbiome and broader physiological indicators, such as antioxidant metabolism and stress-related metabolic processes, are still underexplored. Additionally, the dispersion of studies across different crops, management systems, and edaphoclimatic conditions hinders the consolidation of the effects of these fertilizers. In this scenario, a synthesis of the available scientific evidence becomes necessary. Therefore, our objective in this systematic review was to gather, analyze, and synthesize scientific evidence on the effects of OMFs as a P source in maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L. and *Vigna unguiculata*) crops, which are agronomically relevant and represent contrasting physiological groups (C4 and C3 metabolism), allowing the evaluation of organomineral fertilization under distinct nutrient uptake and metabolic conditions, with emphasis on PUE, plant physiological responses, and soil chemical, physical, and biological attributes, following PRISMA guidelines.

2. Methodology of Data Collection

The systematic review was conducted in accordance with the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [16]. The PRISMA 2020 Checklist used for reporting is provided in the Supplementary File. The guiding research question was structured based on the PICO strategy, considering: (i) Population: maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L. and *Vigna unguiculata*); (ii) Intervention: application of organomineral fertilizers containing phosphorus; (iii) Comparator: conventional mineral fertilizers, such as single superphosphate, triple superphosphate, monoammonium phosphate, and diammonium phosphate; and (iv) Outcome: agronomic and physiological efficiency of P use, as well as changes in soil attributes and the microbiome. Accordingly, the formulated research question was: What are the effects of using OMFs compared to conventional mineral fertilizers, on phosphorus use efficiency, plant metabolism, and soil attributes in maize and bean?

The bibliographic search was conducted in the Scopus, Web of Science, ScienceDirect, SciELO, and Google Scholar databases, considering articles published between 2015 and 2025. The search strategy used English descriptors combined with the Boolean operators AND and OR, applied in a standardized manner across the databases, with technical adjust-

ments when necessary. The terms used were: (“organomineral fertilizer” OR “organomineral phosphate”) AND (“phosphorus use efficiency” OR “PUE”) AND (“maize” OR “corn” OR “*Zea mays*” OR “bean” OR “*Phaseolus vulgaris*” OR “*Vigna unguiculata*”).

Studies were included if they met the following criteria: (i) experiments conducted with maize and/or bean; (ii) use of organomineral fertilizers as a phosphorus source; (iii) presence of a comparative treatment with conventional mineral fertilizers; and (iv) evaluation of at least one of the following outcomes: phosphorus use efficiency, plant physiological parameters such as photosynthesis, growth, gas exchange, or antioxidant metabolism, or chemical, biological, or physical soil attributes. Exclusion criteria were review articles, conference abstracts, book chapters, non-peer-reviewed academic works (such as course completion projects, dissertations, and theses), studies conducted exclusively in nutrient solution without plants, studies that did not address P as the main nutrient, studies that did not use organomineral fertilizers, and publications without full-text access.

The study selection process was carried out by two independent reviewers, starting with the reading of titles and abstracts for initial screening, followed by full-text reading of potentially eligible articles. Inclusion and exclusion criteria were then applied, and relevant data from the selected studies were extracted in a standardized manner. Any discrepancies between the reviewers were resolved by consensus. The entire process of identification, screening, eligibility, and inclusion of articles was summarized using a PRISMA flowchart.

Data from the included studies were organized in a spreadsheet containing bibliographic information (authors, year, and country), experimental characteristics (crop evaluated, study type, soil taxonomic class, and texture), description of the fertilizers used (organic matrix, associated mineral source, and comparative mineral fertilizer), and outcomes assessed.

No formal assessment of risk of bias was performed for the included studies, as the review was descriptive and exploratory in nature, focusing on the identification of general trends and knowledge gaps. The results were synthesized qualitatively through descriptive comparison of the main findings related to P use efficiency, plant physiological responses, and soil attributes. No formal assessment of publication bias or certainty of evidence was conducted, and these limitations were considered in the interpretation of the results. This systematic review was not previously registered, and no protocol was published.

3. Results and Discussion

3.1. General Characteristics of the Included Studies

The search across the databases initially identified 352 records. After applying the identification, screening, and eligibility stages, 39 studies met all the defined criteria and were included in the qualitative synthesis. The complete study selection process is presented in the PRISMA flowchart (Figure 1).

Publications were infrequent between 2015 and 2019, but increased from 2020 onward, reaching a peak in 2023 (Figure 2). The peak observed in 2023 temporally coincides with the instability in the international fertilizer market recorded in 2022, marked by a sharp increase in mineral fertilizer prices as a consequence of the war between Russia and Ukraine. Considering the time lag between experimental work, manuscript submission, and publication, it is plausible that part of the research stimulated by this context was published in the subsequent year. Although descriptive analysis does not allow causal inference, the temporal convergence suggests that economic and geopolitical factors may have contributed to the recent intensification of research on alternative P sources.

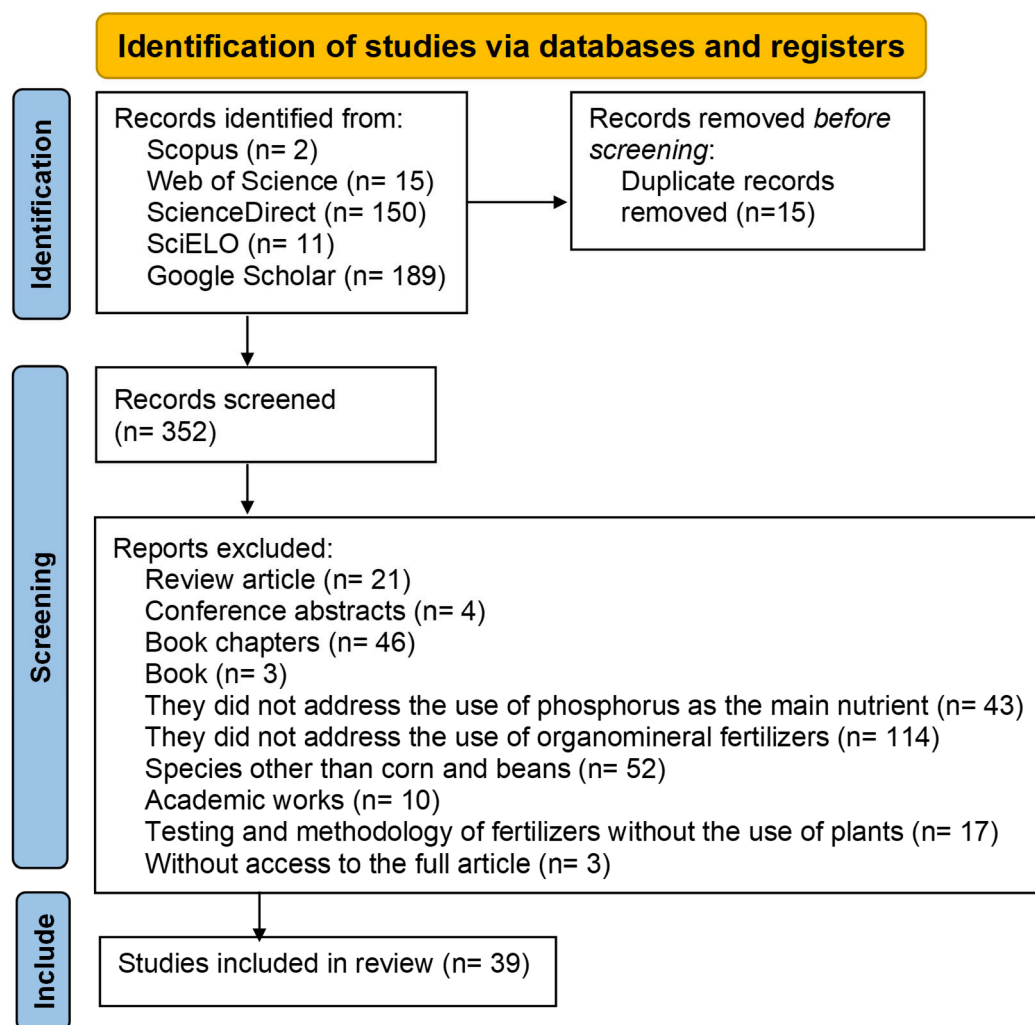


Figure 1. PRISMA flowchart of the study selection process.

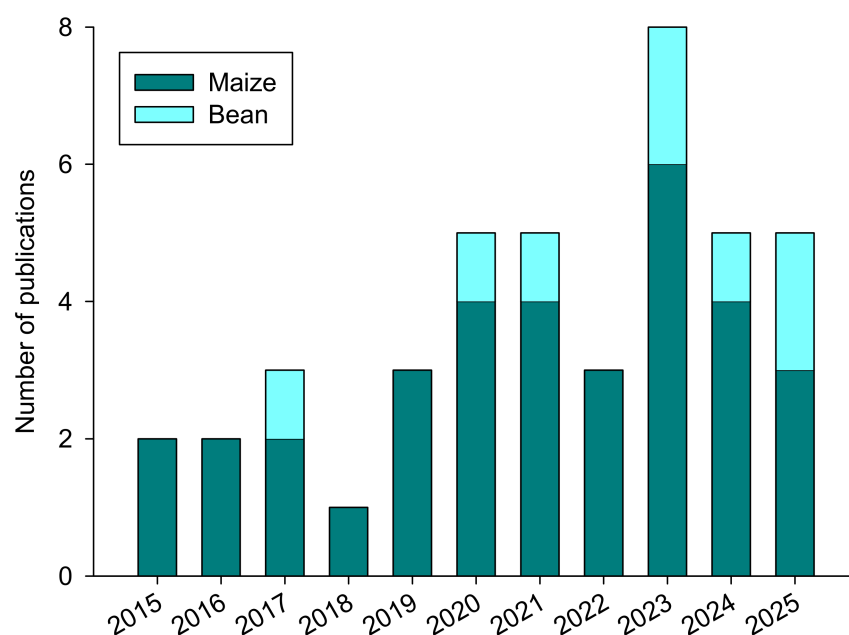


Figure 2. Annual total number of publications on organomineral fertilizers as phosphorus sources for maize and bean from 2015 to 2025.

The distribution of studies by journal shows dispersion across different scientific outlets, with a higher concentration in journals whose scope is related to soil fertility, plant nutrition, sustainable management, and the valorization of organic residues (Figure 3). The journals with the highest number of publications focus on agricultural sustainability, nutrient use efficiency, and more circular production systems, indicating that the discussion on OMFs has been predominantly framed within the context of sustainable agricultural intensification. Thus, the topic appears to be consolidating within a scientific field oriented toward PUE.

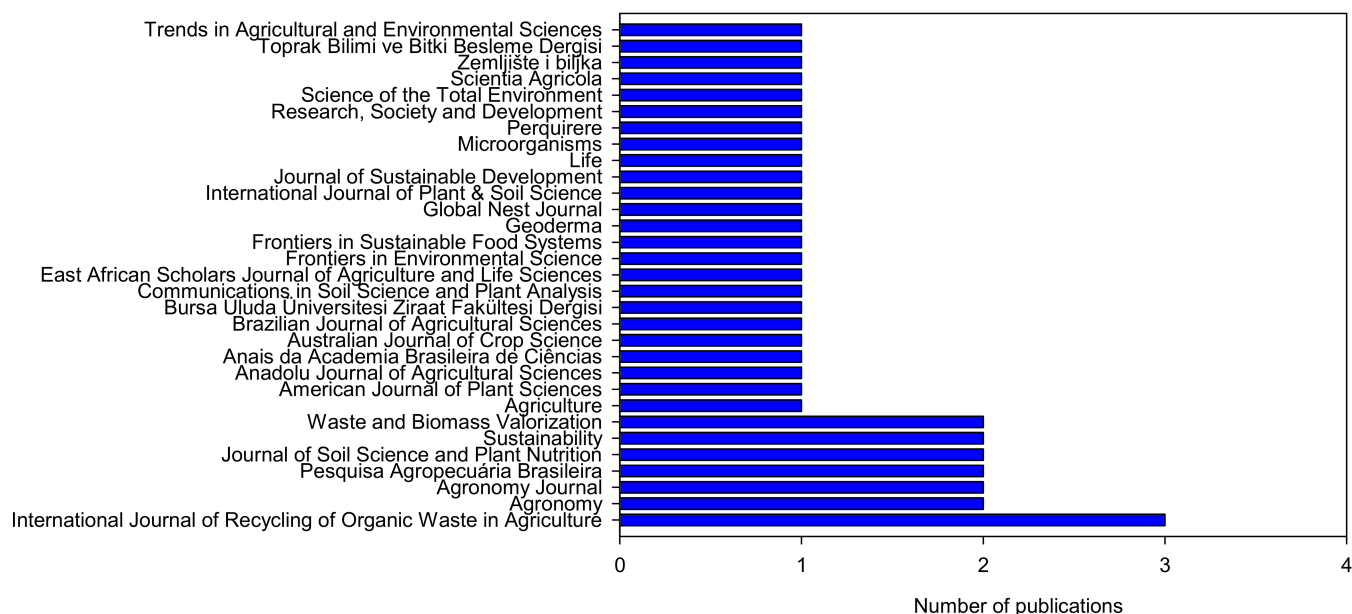


Figure 3. Journal-wise distribution of studies addressing organomineral fertilizers as phosphorus sources for maize and bean over the period 2015–2025.

The included studies were conducted in countries across different climatic zones, encompassing tropical, subtropical, and temperate regions (Figure 4). A higher concentration of studies was observed in tropical and subtropical countries, such as Brazil, Indonesia, Nigeria, Pakistan, and Turkey, where a large proportion of soils exhibit a high capacity for P adsorption, particularly in highly weathered regions, which justifies the interest in studying alternative sources capable of increasing P use efficiency [10,17–20]. In this context, Brazil stood out by accounting for more than half of the studies on OMFs as a P source.

In temperate-climate countries, such as Germany, Poland, and Denmark, the studies identified were not associated with soil P limitation, but rather with environmental and regulatory restrictions related to excessive nutrient use in agricultural areas. In these countries, agricultural intensification has been linked to eutrophication of water bodies, which has motivated policies to reduce the application of soluble mineral P fertilizers and encouraged the evaluation of alternatives with higher agronomic efficiency [21–24].

Of the 352 studies initially identified, 52 were excluded because they did not use maize or bean as test crops. Among the studies included in the systematic review, most were conducted with maize, while only a few used bean as the experimental plant [25–30]. Only 8% of the studies had both crops within the same experiment (Figure 5). This result highlights the need for more studies involving bean and shows that few studies assess, within a single experiment, the effects of OMFs on crops with distinct metabolic characteristics.



Figure 4. Geographic distribution of the studies included in the systematic review.

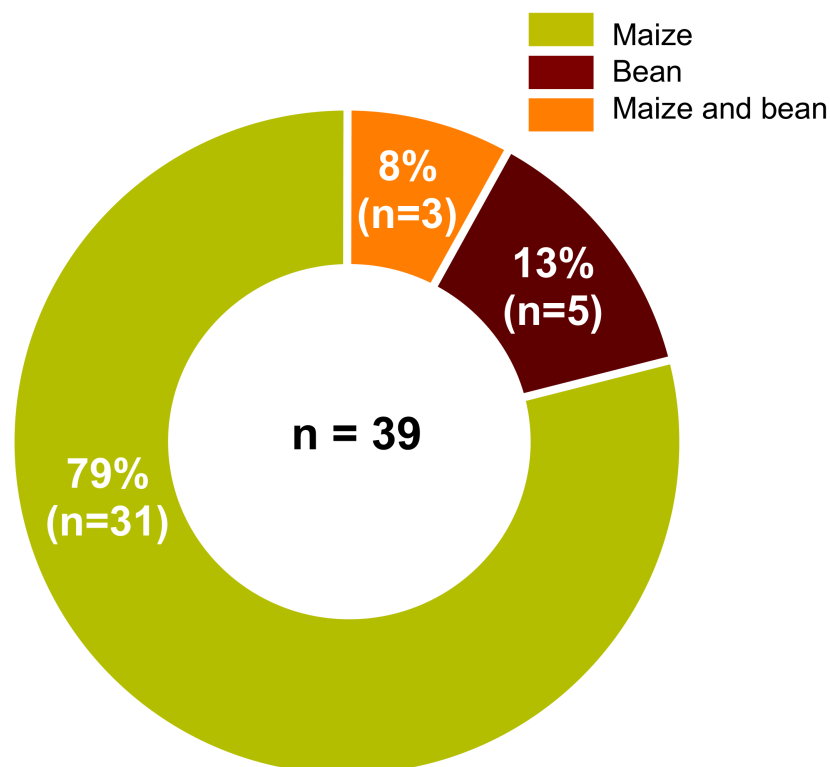


Figure 5. Percentage distribution of studies conducted with maize, bean, or both crops among the 39 studies included in the review.

Regarding the characteristics of the fertilizers evaluated, a wide diversity of organic matrices used in the formulation of OMFs was observed, with a predominance of residues of animal origin, especially poultry litter, which was widely used in studies conducted in Brazil. In contrast, all studies carried out in Germany used oilseed cake and bone meal as

the organic matrix, indicating that the choice of organic residue is related to the regional availability of materials (Figure 6).

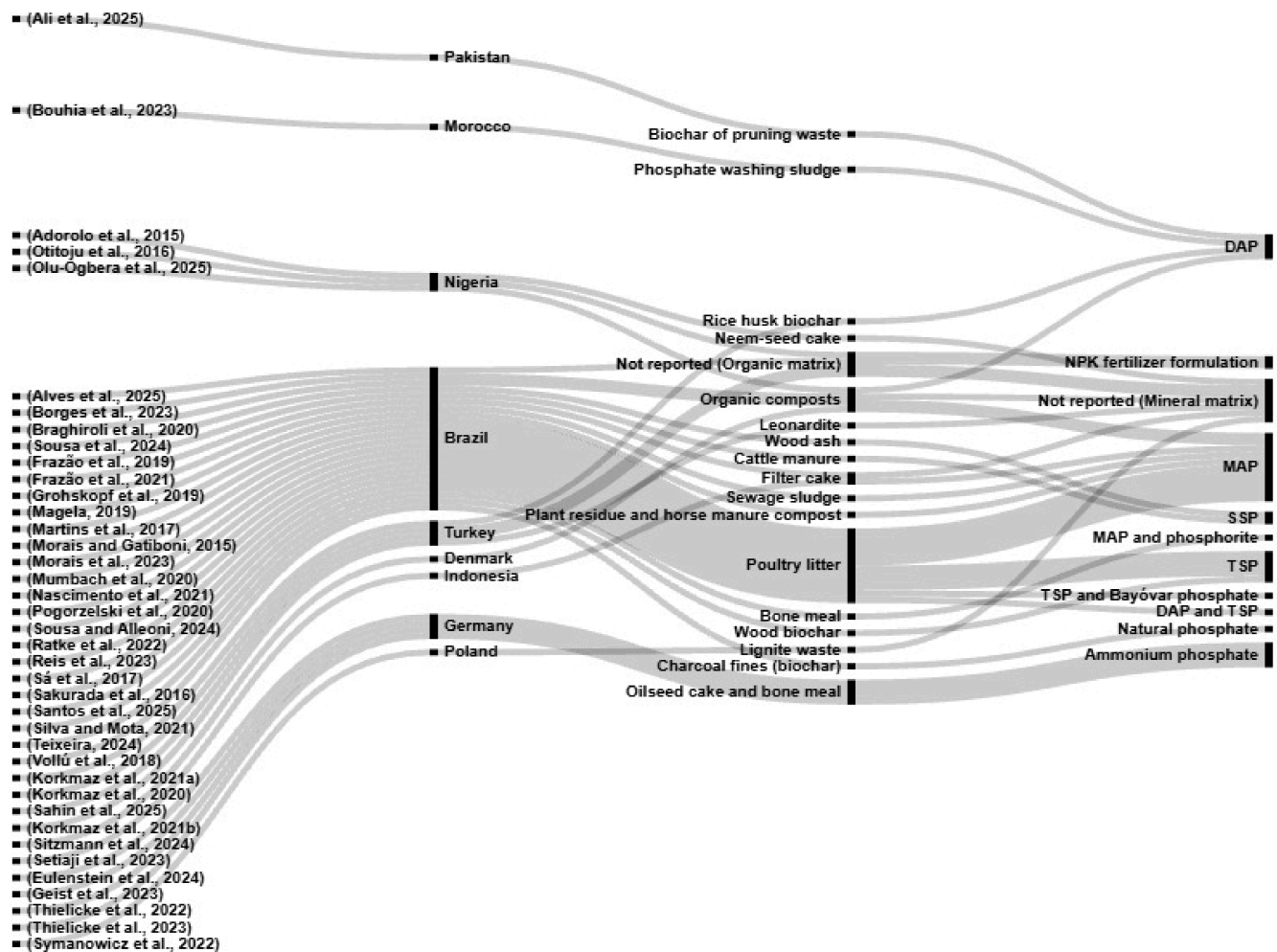


Figure 6. Sankey diagram depicting the relationships among countries, the organic matrices used in organomineral fertilizers, and the mineral phosphorus sources employed in the formulations. The width of each flow is proportional to the number of studies reporting a given combination. Mineral P sources are identified as DAP (diammonium phosphate), MAP (monoammonium phosphate), TSP (triple superphosphate), and SSP (single superphosphate). [7,9,10,17–52].

In most of the studies evaluated, the mineral sources used in the formulation of the organomineral corresponded to soluble phosphate fertilizers, such as monoammonium phosphate (MAP), diammonium phosphate (DAP), single superphosphate (SSP), and triple superphosphate (TSP), with MAP being the most frequently used source (Figure 6). In addition, most researchers used, as the comparative fertilizer, the same mineral source employed in the composition of the organomineral.

The studies were predominantly conducted in agricultural soils typical of humid tropical regions, mainly highly weathered soils, with a predominance of Oxisols and a wide range of textures, from sandy to clayey. Regarding the type of study, evaluations of OMFs have been performed both under controlled conditions and in field conditions, with no marked difference in frequency between these two types of experiments (Figure 7).

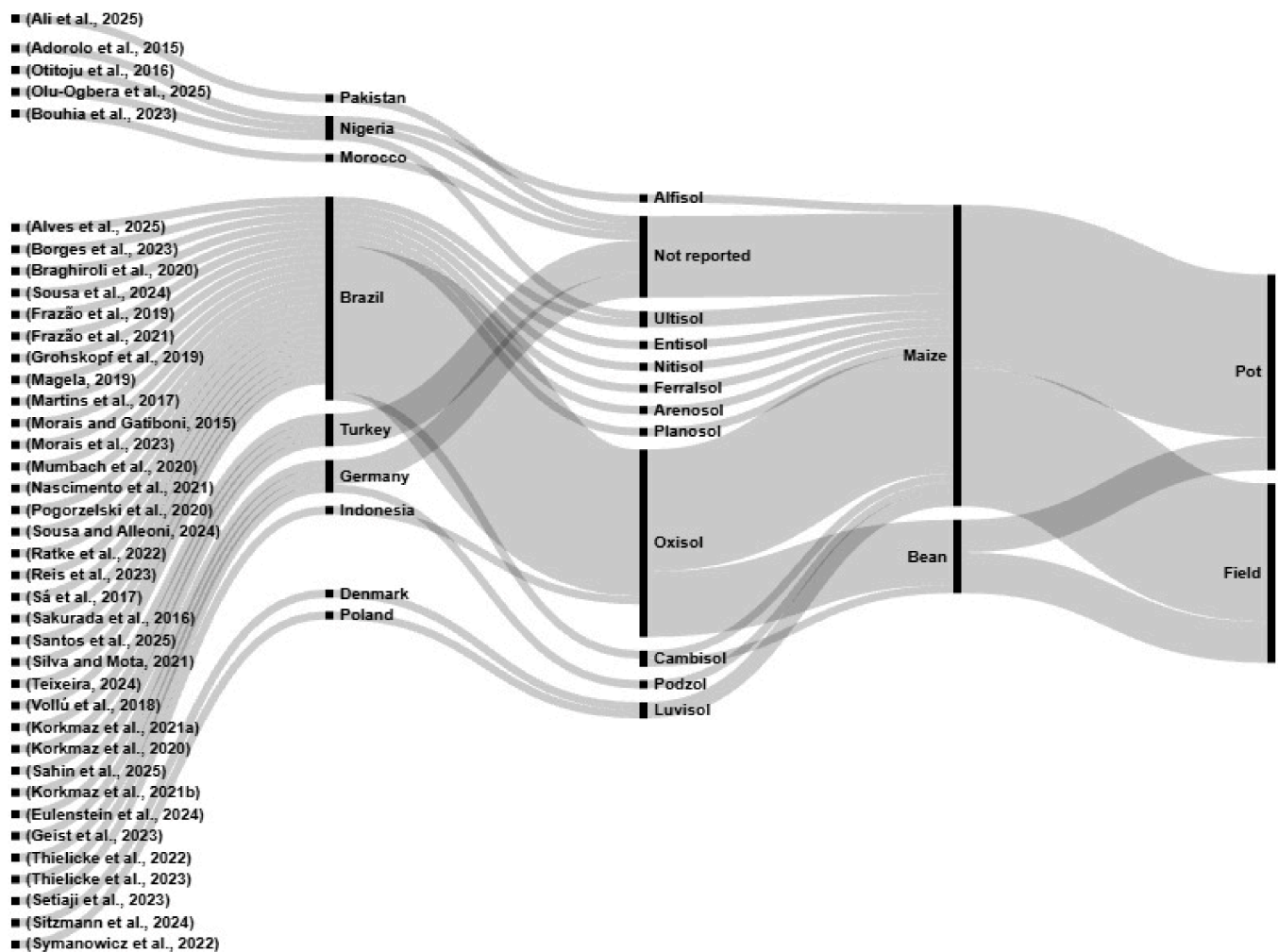


Figure 7. Sankey diagram representing the relationships among the countries where the studies were conducted, the soil classes evaluated, the crops studied, and the type of experiment adopted (pot or field). The width of each flow is proportional to the number of studies reporting a given combination). [7,9,10,17–52].

3.2. Effects of Organomineral Fertilizers on Phosphorus Use Efficiency

Even with fertilizer use, P use efficiency by crops is considered low, ranging from about 10 to 20%, while most of the applied nutrient either remains immobilized or is lost through precipitation, complexation, or leaching into surface waters [53]. Sandy soils with low organic matter contents are common in tropical regions, and P retention is low, but its availability also tends to be limited by low organic inputs and reduced biological cycling. In this context, labile organic carbon plays an important role by serving as an energy source for microorganisms that contribute to the release of P retained in the soil [54].

Given the low efficiency of P utilization from mineral sources, the use of OMFs may represent an alternative. In this context, PUE becomes an important indicator for evaluating the performance of these fertilizers because it is the amount of biomass or yield produced per unit of P absorbed by the plant. PUE allows comparisons among fertilizer sources and identifies those that supply P more effectively [55–57]. Among the 39 studies included in this systematic review, only 14 showed PUE or related metrics, using agronomic efficiency, recovery efficiency, physiological efficiency, and relative agronomic effectiveness (Table 1).

Table 1. Metrics and equations used to calculate phosphorus use efficiency and related indicators in the selected studies.

Reference(s)	Metric	Equation
[31]	Phosphorus use efficiency (PUE)	$[(P \text{ uptake in treatment pot} - P \text{ uptake in control pot}) / (P \text{ rate applied})]$
[33]	Phosphorus agronomic efficiency (PAE)	$[(\text{shoot dry weight of the organomineral fertilizer treatment} - \text{shoot dry weight of the control}) / (P \text{ rate applied})]$
[7]	Relative agronomic effectiveness (RAE)	$[(\text{yield with organomineral fertilizer} - \text{yield with triple superphosphate}) / (\text{yield in control (without P)})] \times 100$
[10]	Relative agronomic effectiveness (RAE)	$[(\text{yield with organomineral fertilizer} - \text{yield with triple superphosphate}) / (\text{yield in control (without P)})] \times 100$
[49]	Phosphorus use efficiency (PUE)	$[(\text{total P accumulated in the aboveground biomass (silage)} - P \text{ accumulated in the treatment without phosphate fertilization}) / (\text{amount of P applied via fertilizer})] \times 100$
[9]	Agronomic efficiency index (AEI)	$[(\text{yield}_{\text{organomineral}} - \text{yield}_{\text{control}}) / (\text{yield}_{\text{mineral}} - \text{yield}_{\text{control}})] \times 100$
[47]	Agronomic Efficiency (AE); Physiological efficiency (PE); Recovery efficiency (RE)	$AE = [(\text{grain yield (corrected)}) / (\text{amount of } P_2O_5 \text{ applied via fertilizer} + \text{amount of } P_2O_5 \text{ present in the soil})]$ $PE = [(\text{grain yield (corrected)}) / (\text{amount of } P_2O_5 \text{ removed by the crop})]$ $RE = [(\text{amount of } P_2O_5 \text{ removed by the crop}) / (\text{amount of } P_2O_5 \text{ applied via fertilizer} + \text{amount of } P_2O_5 \text{ present in the soil})] \times 100$
[41]	Phosphorus utilization efficiency (PUE)	$[(\text{final yield (maize shoot dry biomass)}) / (P \text{ amount in the soil before fertilization} + \text{applied P amount in the fertilizer})]$
[42]	Agronomic Efficiency (AE); Recovery efficiency (RE)	$AE = [(\text{production of dry matter with P} - \text{production of dry matter without P}) / (\text{amount of P applied})]$ $RE = [(P \text{ accumulated with P} - P \text{ accumulated without P}) / (\text{amount of P applied})]$
[43]	Phosphorus use efficiency index (PUEI)	$[(\text{shoot dry matter in the treatment} - \text{shoot dry matter in the control treatment (without P application)}) / (\text{applied P rate})]$
[50]	Apparent recovery efficiency (ARE)	$[(\text{nutrient uptake in the fertilized treatment} - \text{nutrient uptake in the control}) / (\text{amount of nutrient applied})] \times 100$
[51]	Phosphorus use efficiency (PUE)	$[(P \text{ uptake in the treatment} - \text{mean P uptake in the } N_0P_0 \text{ control}) / (P \text{ application rate})] \times 100$
[52]	Phosphorus agronomic efficiency (PAE)	$[(\text{yield in the fertilized treatment} - \text{yield in the control without fertilization}) / (P \text{ application rate})]$
[46]	Agronomic Efficiency (AE); Recovery efficiency (RE)	$AE = [(\text{corrected grain yield}) / (\text{amount of } P_2O_5 \text{ present in the soil and applied via fertilizer})]$ $RE = [(\text{amount of } P_2O_5 \text{ taken up by the plant}) / (\text{amount of } P_2O_5 \text{ present in the soil and applied via fertilizer})]$

There are several calculation methods used to interpret P use efficiency, which makes comparisons among results and experiments difficult [55]. The results of this review show that, although different metrics were applied, most studies (11 out of 14) [9,10,31,33,42,43,46,47,49,50,52] reported that the application of OMFs increased PUE compared with conventional mineral fertilizers, indicating that OMFs can improve the utilization of applied P (Figure 8). The remaining three studies indicated that the response

can be influenced by soil characteristics, crop type, and the composition of the organomineral product. For example, Frazão et al. (2019) [7] observed that, in different soil types, PUE did not differ significantly in Oxisol and was lower in Entisol. Similarly, Sousa and Alleoni (2024) [41] reported that PUE was higher in sandy soils but did not differ in clayey soils. In addition, Sitzmann et al. (2024) [51] showed that the type of organic matrix in the OMFs influenced the results, with the peat-based organomineral fertilizer increasing PUE, whereas products derived from bio-residues resulted in lower efficiency.

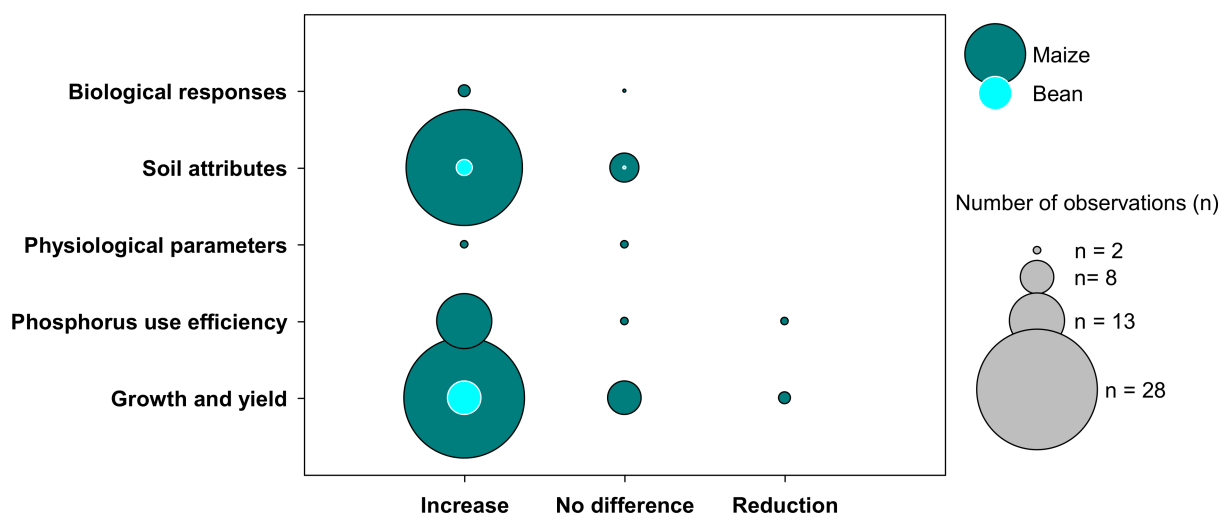


Figure 8. Frequency of reported effects of organomineral fertilization compared to mineral sources in maize and bean. Bubble size represents the number of observations reported for each attribute category and effect direction. Colors indicate crop type.

In addition to the differences related to soil type and the composition of OMFs, the results show that the applied P rates also directly influence nutrient use efficiency indices. The response of PUE to OMFs varied according to the amount of P applied and the parameter used to evaluate efficiency. The influence of P rates on efficiency indices was evidenced by Frazão et al. (2021) [10], who observed distinct responses of OMF compared to SSP as the applied rates increased. In maize, OMF promoted increases of approximately 11% in relative agronomic efficiency based on shoot dry matter production and 50% in the index based on P uptake compared to SSP. However, at lower P rates (17.5 and 35 kg P ha⁻¹), SSP showed greater biomass production, whereas at higher rates OMF showed superior performance. Furthermore, although P uptake was similar between OMF and SSP under part of the evaluated conditions, the fitted regression model indicated a greater increase in P uptake with increasing rates in the OMF treatment, especially at the highest P rates. Similar results were observed by Grohskopf et al. (2019) [9], who evaluated the agronomic efficiency index (AEI) based on maize grain yield in a soil with high initial P content. Grohskopf et al. (2019) [9] verified that poultry litter-based OMF presented AEI values higher than those of MAP at practically all evaluated rates, being, on average, about 20% more efficient over three cropping seasons. However, at the lowest applied rate (20 kg P ha⁻¹), MAP showed greater efficiency in one of the evaluated seasons. These results show that the response of efficiency indices may vary according to P availability in the system and the characteristics of the organomineral formulation.

Bouhia et al. (2023) [33] observed that increasing the proportion of organic matter in organomineral formulations promoted an increase of up to 72% in PUE in fertilizers formulated with DAP and up to 53% and 45% in formulations containing rock phosphate and phosphate residues, respectively. Bouhia et al. (2023) [33] also verified that higher proportions of organic matter increased P solubilization and availability in the soil. How-

ever, the PUE response varied according to the phosphate source used in the formulation, demonstrating that the efficiency of OMF depends on the organic matrix and the solubility of the mineral P source, a result also observed by Sitzmann et al. (2024) [51].

Korkmaz et al. (2021) [46] also observed variation in indices related to P use efficiency according to fertilizer source and applied rate. The authors verified greater P uptake efficiency in OMF derived from animal residues compared to mineral sources, even under reduced P rates. In addition, the highest silage maize yield was obtained with the application of the OMF corresponding to 60% of the recommended P rate, indicating that the OMF maintained good efficiency even with lower P input. Similar results were observed by Sousa and Alleoni (2024) [41], who attributed the better performance of OMF to the gradual release of P and the greater synchronization between nutrient availability in the soil and plant demand throughout the crop cycle. According to Sousa and Alleoni (2024) [41], and Setiaji et al. (2023) [50], the organic fraction present in fertilizers can reduce P adsorption in the soil and favor its maintenance in more available forms, which contributes to greater P utilization and recovery efficiency indices.

The results of the evaluated articles also show that different efficiency metrics may present different responses to OMFs. Some indices are more related to the recovery of applied P, whereas others better demonstrate the plant's ability to transform absorbed P into biomass or yield. Thus, the interpretation of P use efficiency varies according to the index used and the conditions evaluated in each study. The studies included in this review show that OMFs can increase P use efficiency compared to conventional mineral fertilizers, but this response varies according to the applied rates, fertilizer composition, and soil and cultivation conditions.

3.3. Plant Growth and Physiological Responses to Organomineral Fertilizers

Most researchers who evaluated growth and yield reported increases in biomass or productivity with the application of OMFs. Among the evaluated studies, positive responses related to plant growth or crop yield were observed in 27 studies, whereas no differences compared to mineral fertilizers were found in five studies, and reduced productivity was reported in one study (Figure 8). These results show that P supply from OMFs is, in most cases, sufficient to sustain the biosynthetic processes associated with plant growth and development, although the magnitude of the responses varies according to factors such as soil texture, P adsorption capacity, composition of the fertilizer organic matrix, applied rate, and management practices (Table S1).

Borges et al. (2023) [26] and Sousa and Alleoni (2024) [41] observed greater biomass accumulation in sandy soils following OMF addition, whereas the results did not differ from those obtained with mineral sources in clayey soils. In contrast, Frazão et al. (2019) [7] observed no effect of OMF in Oxisols, while in Entisols there was a reduction in productivity, indicating that soil mineralogy and buffering capacity directly influence the agronomic efficiency of these fertilizers. In addition to soil characteristics, differences in crop responses were also associated with the organic matrix used in OMF formulations. Sitzmann et al. (2024) [51] reported that peat-based fertilizers showed productivity similar to that obtained with mineral sources, whereas OMF formulated with bio-residues reduced productivity under certain conditions. Overall, the studies indicate that the agronomic efficiency of OMFs depends on P release dynamics, soil adsorption capacity, and the stability of the organic matrix used.

The evaluated studies showed that the agronomic efficiency of OMFs is directly related to the ability of these fertilizers to maintain adequate levels of available P throughout the crop cycle, thereby influencing processes associated with energy metabolism, photosynthesis, and plant biomass accumulation [9,27,31,34]. Under different cultivation conditions, the

productivity increases observed with the use of OMFs were attributed to the gradual release of P and the greater synchronization between nutrient supply and plant demand, especially in highly weathered tropical soils with high P adsorption capacity [17,25,31,34–36,39,40].

In maize, Ali et al. (2025) [31] observed a 20% increase in plant height with the use of a biochar-based OMF compared to DAP. Similar results were reported by Bouhia et al. (2023) [33], in which the OMF promoted an increase greater than 260% in shoot dry mass and approximately 40% in root biomass compared to DAP. In cowpea, Alves et al. (2025) [25] found that grain dry mass was 17% higher in the OMF treatment compared to the exclusively organic source and 69% higher than the treatment with single superphosphate. In contrast, some studies found no differences between organomineral and mineral fertilizers [7,10,22–24,41,47], suggesting that, when P supply is sufficient to meet crop demand, productive performance tends to depend more on the total availability of the nutrient than on the fertilizer source used.

The evaluation of physiological mechanisms related to P acquisition and utilization is still quite limited in studies involving OMFs, although this information is important for understanding how the organic fraction influences nutrient dynamics in the soil and its uptake by plants. Among the studies included in this review, only Vollú et al. (2018) [45] and Frazão et al. (2019) [7] investigated responses associated with P acquisition through acid phosphatase activity, observing increased enzymatic activity following OMF application. These results suggest a possible influence of OMFs on processes related to P cycling and availability in the rhizosphere. However, important variables for understanding nutrient use efficiency, such as root architecture, uptake kinetics, internal P remobilization, and transporter activity, were not evaluated in the other studies.

P deficiency may impair photosynthetic activity and induce oxidative stress in plants, making evaluations related to antioxidant metabolism relevant in studies involving OMFs. The activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) may help to understand how different P sources influence plant physiological responses under nutrient limitation conditions [58]. The regulation of these enzymes may vary depending on species, the severity of deficiency, and the type of fertilizer, and may involve either increases or decreases in antioxidant activity. However, the activity of these antioxidant enzymes was not included in the studies included in this review, which limits the understanding of the physiological mechanisms associated with the responses observed under organomineral fertilization.

Among the analyzed studies, only four performed physiological evaluations, all in C4 plants (maize), with no studies involving beans [31,33,48,50]. In general, these studies were limited to chlorophyll analysis, and only Sahin et al. (2025) [48] also evaluated leaf anthocyanin content, observing increased chlorophyll associated with reduced anthocyanin levels. Bouhia et al. (2023) [33] and Setiaji et al. (2023) [50] found no differences between organomineral and mineral fertilizers in the evaluated physiological parameters, whereas Ali et al. (2025) [31] reported an increase in chlorophyll content (Figure 8).

Chlorophyll is directly related to the plant's ability to perform photosynthesis and produce biomass, and its concentration depends on an adequate supply of nutrients, especially P and N [48]. In some studies, no differences were observed between fertilizer sources, which may indicate that photosynthetic activity is not limited by the type of fertilizer used when P is present at adequate levels in the soil. In the study that reported increased chlorophyll and reduced anthocyanins, Sahin et al. (2025) [48] attributed this effect to the greater availability and uptake of P provided by biochar-based OMF, which resulted in reduced expression of deficiency symptoms and better physiological performance of the plants.

Interactions between P and other nutrients, such as N, K, Zn, and Fe, may modify crop responses to OMFs, especially in tropical soils with high P adsorption capacity [59–64]. Although these interactions are physiologically relevant, the studies analyzed focused mainly on agronomic variables, without exploring these nutritional relationships at the physiological level.

The results of this review show that OMFs are generally able to sustain crop growth and productivity at levels similar to or higher than those of mineral sources, especially in soils with a high capacity for P adsorption. However, the physiological responses associated with these effects remain poorly explored, as most studies are limited to the evaluation of chlorophyll-related parameters, without considering antioxidant metabolism, gas exchange, and other relevant physiological pathways. Therefore, further studies integrating physiological and yield-related variables are still needed in order to elucidate the mechanisms that regulate plant responses to organomineral P fertilization.

3.4. Effects on Soil Attributes

Most researchers observed effects of OMFs on soil chemical properties compared with mineral sources (Figure 8). OMFs promoted increases in the availability of macronutrients and micronutrients, especially P, calcium (Ca), magnesium (Mg), Zn, boron (B), manganese (Mn), and Fe, in addition to improving the uptake of these nutrients by plants.

In a large proportion of the studies, greater P availability in the soil or a stronger residual effect of this nutrient was observed when OMFs were applied. Pogorzelski et al. (2020) [40] worked with clayey and sandy Oxisols, and attributed this behavior to the slower release kinetics of P compared with soluble mineral fertilizers, with the lower initial release being associated with the physical protection of P by the organic matrix of the OMFs. Similarly, Morais et al. (2023) [37] demonstrated that a more gradual P release in an Oxisol, compatible with plant nutritional demand, represents an efficient strategy to reduce P fixation in the soil and to increase its availability and uptake by crops. This effect was evident in highly weathered soils with a high capacity for P adsorption, such as Oxisols, in which organomineral sources reduced P fixation and increased its availability over time. In some cases, higher P accumulation in roots and higher nutrient recovery indices were also observed [34].

Regarding soil pH, most researchers reported no differences between organomineral and mineral fertilizers. However, Morais et al. (2023) [37] evaluated Oxisols cultivated with maize and observed an increase in pH with the application of OMF compared with MAP, especially in formulations with a higher proportion of organic residue compared with those with a lower proportion. In this study, Morais et al. (2023) [37] detected a positive correlation between pH and the amount of organic N added via fertilizer, indicating that the greater input of the organic fraction was associated with modulation of soil acidity. This result was accompanied by increases in base saturation and in exchangeable Ca and Mg contents.

Ali et al. (2025) [31], Bouhia et al. (2023) [33], Martins et al. (2017) [35], and Olu-Ogbera et al. (2025) [32] reported increases in soil organic carbon and in residual concentrations of N, P, and K after the application of OMFs. However, no differences between sources with respect to total nutrient contents in the soil or P were observed in six studies [9,22,36,38,39,44].

Phosphorus fractionation as affected by the application of OMFs was evaluated in only two studies, indicating that this topic is still poorly explored. In a soil incubation study, Sitzmann et al. (2024) [51] observed that OMF application altered the distribution of P among soil fractions compared with soluble mineral sources, with differences related to the organic material used in the formulation. Peat-based OMF had higher P contents in labile

fractions, whereas OMF formulated with organic residues showed a greater proportion of P in the residual fraction, associated with less available forms.

Similarly, Frazão et al. (2019) [7] compared a phosphate OMF with TSP in an Oxisol and an Entisol, and found increases in labile and moderately labile fractions relative to the control in both soils. In the Entisol, the OMF presented lower P contents in labile fractions compared with TSP, whereas the differences between sources were smaller in the Oxisol. In both studies, non-labile fractions were not altered by the P source, indicating that the use of OMFs mainly affects the more dynamic P fractions in the soil.

Few researchers evaluated attributes related to the soil physical–hydrological behavior, such as water retention capacity and nutrient leaching. In these cases, OMFs increased soil water retention and reduced nutrient leaching, resulting in greater residual availability of P and K. These effects may be related to the role of organic matter in improving soil structure and ion retention, which contributes to higher nutrient use efficiency [37].

Sousa et al. (2025) [65] investigated the P miscible displacement and availability in sandy loam and clayey Oxisols on an experimental column setup, focusing on the influence of soil pH and P sources (organomineral and triple superphosphate). The authors observed that at pH 4.8, OMF solution led to higher Peclet numbers and retardation factors than TSP. However, at pH 6.0, while the differences between OMF and TSP become less pronounced, TSP exhibited slightly higher values, indicating subtle differences in transport dynamics between the two P sources at this higher pH.

None of the articles included in this review addressed structural physical soil attributes, as the selected studies focused on crop responses and the evaluation of chemical and nutritional attributes. This outcome may be related to the selection criteria adopted, in which only studies conducted with maize or bean crops were included. Studies aimed at evaluating soil physical attributes as affected by fertilizer application do not always involve crops, which may explain their exclusion during the selection process.

Overall, OMFs performed similarly to or better than mineral sources in terms of nutrient availability in the soil, especially with respect to P and its residual effect. These responses varied among studies depending on soil conditions and the composition of the organic matrix. Specific aspects of soil P dynamics, such as its distribution among different forms, have been little studied, and physical soil attributes remain underexplored in the context analyzed, highlighting that these are topics that deserve further attention in future research.

In addition to soluble mineral sources used in organomineral fertilizers, the interaction between organic matrices and low-solubility mineral amendments such as rock powders may also influence soil attributes. Organic matter can stimulate microbial activity and organic acid production, potentially enhancing mineral weathering and the gradual release of nutrients [66–68]. Although not directly addressed in the studies included in this review, this approach represents a complementary strategy to improve long-term nutrient availability and soil fertility in highly weathered tropical soils.

3.5. Soil Biological Attributes and Microbiome Responses

Soil fertility does not depend only on physical and chemical properties; biological attributes also play a fundamental role in plant growth and ecosystem functioning. The application of fertilizers, especially OMFs, can alter these conditions, thereby influencing microbial activity and microbiome composition [15,69,70]. Despite this, few studies showed the effects of these fertilizers on soil microbiota: of the 39 studies included in this systematic review, only four addressed biological attributes, and only two evaluated the microbiome using molecular techniques, such as soil DNA extraction and qPCR (Figure 8).

Among the few studies that investigated microbiological responses, Sitzmann et al. (2024) [51] showed that OMF application affected microbial activity and nutrient availability in the soil in a manner dependent on the origin of the organic matter. All OMFs increased microbial respiration (released CO₂) and ammonia emission (volatilized NH₃) compared with the mineral control, indicating that the addition of organic carbon, even in small amounts, stimulates microbial metabolic activity. However, differences in P and N uptake by maize plants were more strongly influenced by the chemical properties of the organic matrices than by microbial immobilization.

In addition to stimulating microbial activity, OMFs can increase soil microbial population density. Olu-Ogbera et al. (2025) [32] observed that the application of OMF based on neem seeds (*Azadirachta indica* A. Juss.) and organic compounds increased soil bacterial and fungal populations compared with the control. According to Olu-Ogbera et al. (2025) [32], this effect is due to the organic matter present in OMF, which improves nutrient availability, porosity, and soil stability, creating favorable conditions for microbial activity. In contrast, mineral fertilizer reduced bacterial populations, probably due to the lower supply of substrates for microorganisms.

OMFs also influence enzymatic processes that are important for P cycling. Vollú et al. (2018) [45] evaluated the effects of OMF in the maize rhizosphere by analyzing P-mineralizing bacteria, phosphatase and phytase activities, and quinolone resistance genes (qnr). The authors observed that the addition of an OMF composed of TSP combined with poultry sludge increased phytase activity, indicating greater release of organic P to plants; however, there were no changes in the abundance of phosphate-mineralizing bacteria or in the overall diversity and composition of the microbiome, which varied more with plant age and the amount of fertilizer applied. Quinolone resistance genes were not detected, and fluoroquinolone concentrations in the soil remained below the limit of quantification, showing that OMF application did not increase microbiological risks.

Geist et al. (2023) [22] investigated the effects of microgranulated organomineral fertilizers on the soil microbiome using molecular techniques such as DNA extraction and qPCR to quantify microbial abundance and community composition. The authors observed that OMF application increased the abundance of *Bacillus atrophaeus* Abi05, favored beneficial microorganisms, and reduced the relative proportion of *Fusarium*, without changing the overall microbiome diversity. These effects were attributed to the presence of organic substrates in OMFs, which promote microbial competition and shifts in the functional structure of the community, similarly to what was observed by Vollú et al. (2018) [45], indicating that OMFs can modulate microbiota function without altering its diversity; however, further studies are still needed.

4. Conclusions

In this study, scientific evidence on the effects of organomineral phosphate fertilizers on phosphorus use efficiency, plant growth, and soil attributes in maize and bean was analyzed. Overall, these fertilizers can perform similarly to or better than conventional mineral sources, especially in soils with a high capacity for P fixation. Most researchers reported increases in biomass and greater P availability in the soil, highlighting the potential of OMFs as an alternative for managing this nutrient.

Despite these positive results, few researchers quantified phosphorus use efficiency, which limits the assessment of fertilizer performance under this criterion. In addition, physiological evaluations were limited and focused mainly on chlorophyll-related parameters, leaving aside important processes such as antioxidant metabolism, gas exchange, and nutritional interactions.

Most studies were conducted with maize, whereas few involved bean, and there are almost no studies comparing physiological responses between C4 and C3 plants under organomineral fertilization. In addition, differences in agronomic management practices among the studies, including fertilization rates, application methods, irrigation conditions, and soil management systems, may also have contributed to the variability of the observed responses. However, these variables were not consistently reported in the available literature, limiting more detailed comparisons among experiments.

Soil effects were evaluated mainly through chemical attributes, with emphasis on P availability and residual effects. In contrast, aspects such as P fractionation and physical attributes were rarely considered. Biological indicators represent the least explored area, with few studies assessing microbial activity and only a very limited number using molecular tools to characterize the microbiome. Longer-term experiments conducted in different soil classes and with distinct organic matrices are needed to clarify residual effects and P dynamics in the soil.

The evidence indicates that OMFs can contribute to P management in maize and bean production systems, especially when the initial availability of the nutrient is low. However, these findings are based exclusively on studies conducted with maize and bean and should not be generalized to other crops or agricultural production systems. Further progress in this field depends on studies that systematically incorporate the calculation of PUE and integrate chemical, biological, and physiological assessments. Although OMFs represent a promising alternative, their mechanisms of action are not yet fully elucidated. Further research and the expansion of the range of variables evaluated will be decisive for consolidating their use in sustainable phosphorus management.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/soilsystems10070074/s1>, Table S1. Characteristics of the studies included in the systematic review.

Author Contributions: Conceptualization, C.F.O.S. and E.F.S.; methodology, C.F.O.S., C.F.O. and E.F.S.; software, C.F.O.S.; validation, C.F.O.S., C.F.O., L.R.F.A., V.d.M.B. and E.F.S.; formal analysis, C.F.O.S. and C.F.O.; investigation, C.F.O.S. and C.F.O.; resources, C.F.O.S. and E.F.S.; data curation, C.F.O.S. and C.F.O.; writing—original draft preparation, C.F.O.S.; writing—review and editing, C.F.O.S., L.R.F.A., V.d.M.B. and E.F.S.; visualization, C.F.O.S., C.F.O., L.R.F.A., V.d.M.B. and E.F.S.; supervision, E.F.S.; project administration, C.F.O.S. and E.F.S.; funding acquisition, E.F.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financed in part by the Coordination for the Improvement of Higher Education Personnel—Brazil (CAPES)—Finance Code 001.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable.

Conflicts of Interest: Author Vinícius de Melo Benites is employed by the Brazilian Agricultural Research Corporation. Other authors declare no conflicts of interest.

References

1. Shi, Q.; Pang, J.; Yong, J.W.H.; Bai, C.; Pereira, C.G.; Song, Q.; Wu, D.; Dong, Q.; Cheng, X.; Wang, F.; et al. Phosphorus-fertilisation has differential effects on leaf growth and photosynthetic capacity of *Arachis hypogaea* L. *Plant Soil* **2020**, *447*, 99–116. [\[CrossRef\]](#)
2. Baroowa, B.; Paul, S.; Gogoi, N. Role of phosphorus in imparting abiotic stress tolerance to plants. In *Climate Change and Agriculture*; Wiley: Hoboken, NJ, USA, 2022; pp. 239–262. [\[CrossRef\]](#)
3. Hawkesford, M.J.; Cakmak, I.; Coskun, D.; De Kok, L.J.; Lambers, H.; Schjoerring, J.K.; White, P.J. Functions of macronutrients. In *Marschner's Mineral Nutrition of Plants*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 201–281. [\[CrossRef\]](#)
4. Khan, F.; Siddique, A.B.; Shabala, S.; Zhou, M.; Zhao, C. Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants* **2023**, *12*, 2861. [\[CrossRef\]](#) [\[PubMed\]](#)

5. Santos, E.F.; Pongrac, P.; Reis, A.R.; Rabêlo, F.H.S.; Azevedo, R.A.; White, P.J.; Lavres, J. Unravelling homeostasis effects of phosphorus and zinc nutrition by leaf photochemistry and metabolic adjustment in cotton plants. *Sci. Rep.* **2021**, *11*, 13746. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Santos, E.F.; Figueiredo, C.O.; Rocha, M.A.P.; Lanza, M.G.D.B.; Silva, V.M.; Reis, A.R. Phosphorus and selenium interaction effects on agronomic biofortification of cowpea plants. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 4385–4395. [\[CrossRef\]](#)
7. Frazão, J.J.; Benites, V.M.; Ribeiro, J.V.S.; Pierobon, V.M.; Lavres, J. Agronomic effectiveness of a granular poultry litter-derived organomineral phosphate fertilizer in tropical soils: Soil phosphorus fractionation and plant responses. *Geoderma* **2019**, *337*, 582–593. [\[CrossRef\]](#)
8. Benites, V.M.; Corrêa, J.C.; Faria, J.; Menezes, S.; Polidoro, C. *Production of Granular Organomineral Fertilizer From Swine and Poultry Manure in Brazil*; Embrapa Solos: Rio de Janeiro, Brazil, 2013. (In Portuguese)
9. Grohskopf, M.A.; Corrêa, J.C.; Fernandes, D.M.; Benites, V.M.; Teixeira, P.C.; Cruz, C.V. Phosphate fertilization with organomineral fertilizer on corn crops on a Rhodic Khandiudox with a high phosphorus content. *Pesqui. Agropecu. Bras.* **2019**, *54*, e00434. [\[CrossRef\]](#)
10. Frazão, J.J.; Benites, V.M.; Pierobon, V.M.; Ribeiro, J.V.S.; Lavres, J. A poultry litter-derived organomineral phosphate fertilizer has higher agronomic effectiveness than conventional phosphate fertilizer applied to field-grown maize and soybean. *Sustainability* **2021**, *13*, 11635. [\[CrossRef\]](#)
11. Santos, E.F.; Macedo, F.G.; Rodrigues, M.; Pavinato, P.S.; Lavres, J. Low zinc availability limits the response to phosphorus fertilization in cotton. *J. Plant Nutr. Soil Sci.* **2024**, *187*, 375–387. [\[CrossRef\]](#)
12. Araújo, M.D.M.; Souza, H.A.; Benites, V.M.; Pompeu, R.C.F.F.; Natale, W.; Leite, L.F.C. Organomineral phosphate fertilization in millet in sandy soil. *Rev. Bras. Eng. Agríc. Ambient.* **2020**, *24*, 694–699. [\[CrossRef\]](#)
13. Kang, J.; Amoozegar, A.; Hesterberg, D.; Osmond, D.L. Phosphorus leaching in a sandy soil as affected by organic and inorganic fertilizer sources. *Geoderma* **2011**, *161*, 194–201. [\[CrossRef\]](#)
14. Santos, S.R.; Hesterberg, D.; Alleoni, L.R.F. Phosphate speciation and citrate-induced mobilization of P in an Acric Oxisol. *Commun. Soil Sci. Plant Anal.* **2017**, *48*, 1977–1988. [\[CrossRef\]](#)
15. Oliveira, C.F.; Benites, V.M.; Libardi, P.L.; Alleoni, L.R.F. Soil properties and potassium dynamics under the influence of organomineral fertilization in a tropical sandy-loam soil. *J. Soil Sci. Plant Nutr.* **2026**, *26*, 4655–4670. [\[CrossRef\]](#)
16. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Adorolo, M.; Okonokhua, B.; Akinrinde, E. Comparative effects of lime and phosphorus sources on nutrients uptake and yield of maize in a tropical Ultisol. *Int. J. Plant Soil Sci.* **2015**, *4*, 140–148. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Magela, M.L.M.; Camargo, R.; Lana, R.M.Q.; Miranda, M.C.C. Application of organomineral fertilizers sourced from filter cake and sewage sludge can affect nutrients and heavy metals in soil during early development of maize. *Aust. J. Crop Sci.* **2019**, *13*, 863–873. [\[CrossRef\]](#)
19. Otitoju, O.M.; Adewole, M.B.; Olowoake, A.A.; Ilesanmi, A.O. Direct and residual effects of different poultry compost and NPK fertilizer applications on drought-tolerant maize production. *J. Sustain. Dev.* **2016**, *9*, 61. [\[CrossRef\]](#)
20. Ratke, R.F.; Bertechini, M.C.; Figueiredo, C.C.; Arauco, A.M.D.S.; Dias, B.D.O.; Oliveira, J.C.; Zuffo, A.M.; Oliveira-Paiva, C.A.; Santos-Júnior, J.D.D.G.; Roque, C.G. Soil organic matter fractions and enzymes activities under no-tillage system: Effects of organomineral and mineral fertilizer with humic substances. *Commun. Soil Sci. Plant Anal.* **2022**, *53*, 304–316. [\[CrossRef\]](#)
21. Eulenstein, F.; Ahlborn, J.; Thielicke, M. The potential of microgranular fertilizers to reduce nutrient surpluses when growing maize (*Zea mays*) in regions with high livestock farming intensity. *Life* **2024**, *14*, 81. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Geist, L.; Wolfer, R.; Thiem, R.; Thielicke, M.; Eichler-Löbermann, B.; Eulenstein, F.; Müller, M.E.H. Alternative starter fertilization strategies in maize (*Zea mays* L.) cultivation: Agronomic potential of microgranular fertilizer and plant growth-promoting microorganisms and their impact on the soil native microbial community. *Agronomy* **2023**, *13*, 2900. [\[CrossRef\]](#)
23. Thielicke, M.; Ahlborn, J.; Životić, L.; Saljnikov, E.; Eulenstein, F. Microgranular fertilizer and biostimulants as alternatives to diammonium phosphate fertilizer in maize production on marshland soils in northwest Germany. *Zemlj. Biljka* **2022**, *71*, 53–66. [\[CrossRef\]](#)
24. Thielicke, M.; Ahlborn, J.; Eichler-Löbermann, B.; Eulenstein, F. On the negative impact of mycorrhiza application on maize plants (*Zea mays*) amended with mineral and organic fertilizer. *Microorganisms* **2023**, *11*, 1663. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Alves, R.D.S.; Bonfim-Silva, E.M.; Silva, T.J.A.; Oliveira, J.R.; Ribeiro-Santos, J.M.; Meneghetti, A.M.L. Organomineral fertilizer based on wood ash in bean cultivation in acidic tropical soil. *Int. J. Recycl. Org. Waste Agric.* **2025**, *14*, 142531. [\[CrossRef\]](#)
26. Borges, W.L.; Garcia, J.P.; Teixeira, P.C.; Polidoro, J.C. Cowpea, corn, and soybean yield using fertilizer based on the bone meal in the eastern Amazon. *Rev. Bras. Ciênc. Agrár.* **2023**, *18*, e2577. [\[CrossRef\]](#)

27. Sousa, C.H.C.; Zuffo, A.M.; Oliveira, B.R.; Silva, F.C.S.; Mezzomo, R.; Barrozo, L.M.; Zanatta, T.S.C.; Santos, J.C.; Coelho, Y.P.; Caldas, A.N.S. Dataset: Cowpea cultivars with residual organomineral fertilizers from crop corn cultivation. *Trends Agric. Environ. Sci.* **2024**, *2*, e240007. [[CrossRef](#)]
28. Reis, D.R.; Teixeira, G.C.S.; Teixeira, I.R.; Silva, G.R.; Ribeiro, B.B.A. Organomineral fertilization associated with inoculation of *Rhizobium tropici* and co-inoculation of *Azospirillum brasilense* in common bean. *Sustainability* **2023**, *15*, 16631. [[CrossRef](#)]
29. Santos Júnior, J.M.; Colen, F.; Frazão, L.A.; Pegoraro, R.F.; Fernandes, L.A. Granulated organomineral fertilizers from by-products of the agricultural and forestry sector. *Sci. Agric.* **2025**, *82*, e20240132. [[CrossRef](#)]
30. Silva, L.; Mota, H. Organomineral and mineral fertilization in the availability of phosphorus in bean plants. *Rev. Perquirere* **2021**, *18*, 10–22. (In Portuguese)
31. Ali, A.; Ahmad, S.; Ahmed, W.; Ali, M.; Ather, M.; Ismail, A.M.; Alhajhoj, M.R.; Alturki, S.M.; Darrag, H.M.; Al-Khayri, J.M. Conversion of pruning waste into biochar-based organomineral fertilizer to improve maize yield and phosphorus use efficiency. *Glob. Nest J.* **2025**, *27*, 07188. [[CrossRef](#)]
32. Olu-Ogbera, O.A.; Adetomiwa, K.T.; Adejoro, S.A. Soil residual microbial population and chemical fertility following maize cropping as influenced by an organo-mineral fertilizer formulation. *East Afr. Sch. J. Agric. Life Sci.* **2025**, *8*, 20–27. [[CrossRef](#)]
33. Bouhia, Y.; Hafidi, M.; Ouhdouch, Y.; Zeroual, Y.; Lyamlouli, K. Organo-Mineral Fertilization Based on Olive Waste Sludge Compost and Various Phosphate Sources Improves Phosphorus Agronomic Efficiency, *Zea mays* Agro-Physiological Traits, and Water Availability. *Agronomy* **2023**, *13*, 249. [[CrossRef](#)]
34. Braghiroli, R.; Benites, V.M.; Araújo, A.P. Efficiency of Organo-Mineral Fertilizer Enriched with Citric Acid in Corn (*Zea mays* L.) grown in the Greenhouse. *Res. Soc. Dev.* **2020**, *9*, e702974575. (In Portuguese) [[CrossRef](#)]
35. Martins, D.C.; Resende, Á.V.; Galvão, J.C.C.; Simão, E.D.P.; Ferreira, J.P.D.C.; Almeida, G.D.O. Organomineral phosphorus fertilization in the production of corn, soybean and bean cultivated in succession. *Am. J. Plant Sci.* **2017**, *8*, 2407–2421. [[CrossRef](#)]
36. Moraes, F.A.; Gatiboni, L.C. Phosphorus availability and microbial immobilization in a Nitisol with the application of mineral and organo-mineral fertilizers. *An. Acad. Bras. Cienc.* **2015**, *87*, 2289–2299. [[CrossRef](#)] [[PubMed](#)]
37. Moraes, E.G.; Silva, C.A.; Maluf, H.J.G.M.; Paiva, I.O.; Paula, L.H.D. Effects of Compost-Based Organomineral Fertilizers on the Kinetics of NPK Release and Maize Growth in Contrasting Oxisols. *Waste Biomass Valorization* **2023**, *14*, 2299–2321. [[CrossRef](#)]
38. Mumbach, G.L.; Gatiboni, L.C.; Bona, F.D.; Schmitt, D.E.; Corrêa, J.C.; Gabriel, C.A.; Dall'Orsoletta, D.J.; Iochims, D.A. Agronomic efficiency of organomineral fertilizer in sequential grain crops in southern Brazil. *Agron. J.* **2020**, *112*, 3037–3049. [[CrossRef](#)]
39. Nascimento, C.O.; Mattos, B.B.; Dal Molin, S.J.; Fialho, R.L.; Cabral-Albuquerque, E.C.M.; Benites, V.M. Phosphorus diffusion and agronomic efficiency of chicken litter organomineral fertilizers improved with binder materials. *Waste Biomass Valorization* **2021**, *12*, 3765–3772. [[CrossRef](#)]
40. Pogorzelski, D.; Filho, J.F.L.; Matias, P.C.; Santos, W.O.; Vergütz, L.; Melo, L.C.A. Biochar as composite of phosphate fertilizer: Characterization and agronomic effectiveness. *Sci. Total Environ.* **2020**, *743*, 140604. [[CrossRef](#)] [[PubMed](#)]
41. Sousa, R.N.; Alleoni, L.R.F. Performance of Struvite and Organomineral Fertilizers Compared to Traditional Source of Phosphorus in Maize Cultivation on Tropical Soils. *J. Soil Sci. Plant Nutr.* **2024**, *24*, 5250–5271. [[CrossRef](#)]
42. Sá, J.M.; Jantalia, C.P.; Teixeira, P.C.; Polidoro, J.C.; Benites, V.M.; Araújo, A.P. Agronomic and P recovery efficiency of organomineral phosphate fertilizer from poultry litter in sandy and clayey soils. *Pesqui. Agropecu. Bras.* **2017**, *52*, 786–793. [[CrossRef](#)]
43. Sakurada, L.R.; Batista, M.A.; Inoue, T.T.; Muniz, A.S.; Pagliari, P.H. Organomineral Phosphate Fertilizers: Agronomic Efficiency and Residual Effect on Initial Corn Development. *Agron. J.* **2016**, *108*, 2050–2059. [[CrossRef](#)]
44. Teixeira, P.C.; Loiola, J.A.D.; Dias, R.C.; Alonso, J.M.; Zonta, E.; Straliootto, R. Evaluation of different phosphate organomineral fertilizers in maize cultivation on soils with contrasting phosphorus contents. *Int. J. Recycl. Org. Waste Agric.* **2024**, *14*, 142506–142507. [[CrossRef](#)]
45. Vollú, R.E.; Cotta, S.R.; Jurelevicius, D.; Leite, D.C.A.; Parente, C.E.T.; Malm, O.; Martins, D.C.; Resende, Á.V.; Marriel, I.E.; Seldin, L. Response of the Bacterial Communities Associated With Maize Rhizosphere to Poultry Litter as an Organomineral Fertilizer. *Front. Environ. Sci.* **2018**, *6*, 118. [[CrossRef](#)]
46. Korkmaz, A.; Yilmaz, F.; Gezgin, S. Effects of organomineral fertilizers derived from different chemical and organic sources on silage maize yield and phosphorus uptake efficiency. *Bursa Uludag Univ. Ziraat Fak. Derg.* **2021**, *36*, 213–225. (In Turkish) [[CrossRef](#)]
47. Korkmaz, A.; Gezgin, S.; Yilmaz, F. Comparison of the effects of organomineral fertilizer and K-humate on grain maize yield and phosphorus use efficiency with those of chemical fertilizer. *Toprak Bilim. Bitki Besleme Derg.* **2020**, *8*, 137–144. (In Turkish) [[CrossRef](#)]
48. Sahin, O.; Eroglu, N.S.; Gunes, A. Development of Rice Husk Biochar Based Organo-mineral Fertilizers: Determination of their Primary and Residual Efficiency in Silage Maize. *J. Soil Sci. Plant Nutr.* **2025**, *25*, 8753–8765. [[CrossRef](#)]
49. Korkmaz, A.; Gezgin, S.; Yilmaz, F. Effects of different phosphorus applications with organomineral and chemical fertilizers on silage maize yield and phosphorus use efficiency. *Anadolu J. Agric. Sci.* **2021**, *36*, 268–275. (In Turkish) [[CrossRef](#)]

50. Setiaji, A.; Santoso, B.; Wibisono, H. Effect of sugarcane filter cake-based organomineral fertilizers on sweet maize growth. *Int. J. Recycl. Org. Waste Agric.* **2023**, *12*, 159–177. [\[CrossRef\]](#)
51. Sitzmann, T.J.; Sica, P.; Grignani, C.; Magid, J. Testing biowaste materials as peat replacement in organo-mineral fertilizers. *Front. Sustain. Food Syst.* **2024**, *8*, 1330843. [\[CrossRef\]](#)
52. Symanowicz, B.; Becher, M.; Jaremko, D.; Toczko, M.; Toczko, R.; Krasuski, S. The Delayed Effect of Low-Energy Lignite Organic Matter on the Treatment Optimization of *Zea mays* L. Grown for Silage. *Agriculture* **2022**, *12*, 1639. [\[CrossRef\]](#)
53. Rose, T.J.; Hardiputra, B.; Rengel, Z. Wheat, canola and grain legume access to soil phosphorus fractions differs in soils with contrasting phosphorus dynamics. *Plant Soil* **2010**, *326*, 159–170. [\[CrossRef\]](#)
54. Zhu, J.; Li, M.; Whelan, M. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. *Sci. Total Environ.* **2018**, *612*, 522–537. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Urlić, B.; Dumičić, G.; Radić, T.; Goreta Ban, S.; Romić, M. Phosphorus Use Efficiency of Leafy Brassica sp. Grown in Three Contrasting Soils: Growth, Enzyme Activity and Phosphorus Fractionation. *Plants* **2023**, *12*, 1295. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Guelfi, D.; Nunes, A.P.P.; Sarkis, L.F.; Oliveira, D.P. Innovative Phosphate Fertilizer Technologies to Improve Phosphorus Use Efficiency in Agriculture. *Sustainability* **2022**, *14*, 14266. [\[CrossRef\]](#)
57. Blackwell, M.; Darch, T.; Haslam, R. Phosphorus use efficiency and fertilizers: Future opportunities for improvements. *Front. Agric. Sci. Eng.* **2019**, *6*, 332–340. [\[CrossRef\]](#)
58. Hernández, I.; Munné-Bosch, S. Linking phosphorus availability with photo-oxidative stress in plants. *J. Exp. Bot.* **2015**, *66*, 2889–2900. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Malhotra, H.; Vandana; Sharma, S.; Pandey, R. Phosphorus Nutrition: Plant Growth in Response to Deficiency and Excess. In *Plant Nutrients and Abiotic Stress Tolerance*; Springer: Singapore, 2018; pp. 171–190. [\[CrossRef\]](#)
60. Sárdi, K.; Balázs, Á.; Salamon, B. Interrelations in Phosphorus and Potassium Accumulation Characteristics of Plants Grown in Different Soil Types. *Commun. Soil Sci. Plant Anal.* **2012**, *43*, 324–333. [\[CrossRef\]](#)
61. Tariq, A.; Zeng, F.; Graciano, C.; Ullah, A.; Sadia, S.; Ahmed, Z.; Murtaza, G.; Ismoilov, K.; Zhang, Z. Regulation of Metabolites by Nutrients in Plants. In *Plant Ionomics*; Wiley: Hoboken, NJ, USA, 2023; pp. 1–18. [\[CrossRef\]](#)
62. Mishra, S.; Levengood, H.; Fan, J.; Zhang, C. Plants Under Stress: Exploring Physiological and Molecular Responses to Nitrogen and Phosphorus Deficiency. *Plants* **2024**, *13*, 3144. [\[CrossRef\]](#) [\[PubMed\]](#)
63. Oliveira, C.F.; Fanaya, E.D.; Mateus, N.S.; Lavres, J.; Santos, E.F. Improving zinc supply enhances cotton nutritional phosphorus efficiency. *J. Plant Nutr.* **2023**, *46*, 2451–2461. [\[CrossRef\]](#)
64. Yang, X.; Liu, C.; Liang, C.; Wang, T.; Tian, J. The Phosphorus-Iron Nexus: Decoding the Nutrients Interaction in Soil and Plant. *Int. J. Mol. Sci.* **2024**, *25*, 6992. [\[CrossRef\]](#) [\[PubMed\]](#)
65. Sousa, R.N.; Pessoa, T.N.; Libardi, P.L.; Alleoni, L.R.F. Liming and soil texture affect the miscible displacement of phosphorus from organic and mineral sources in tropical Oxisols. *Sci. Total Environ.* **2025**, *961*, 178341. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Holsback, H.M.S.; Silva, G.N.; Conceição, L.T.; Mattos, L.M.; Marcante, N.C.; França, D.M.; Martins, É.S.; Santos, E.F. The potential of gneiss powder to enhance soil fertility and crop nutrition in agriculture. *Commun. Soil Sci. Plant Anal.* **2026**, *57*, 1–14. [\[CrossRef\]](#)
67. Conceição, L.T.; Silva, G.N.; Holsback, H.M.S.; Oliveira, C.F.; Marcante, N.C.; Martins, É.S.; Santos, L.F.S.; Santos, E.F. Potential of basalt dust to improve soil fertility and crop nutrition. *J. Agric. Food Res.* **2022**, *10*, 100443. [\[CrossRef\]](#)
68. Oliveira, C.F.; Silva, G.N.; Marcante, N.C.; Vasconcelos, V.; Mandro, M.A.E.; Santos, E.F. Assessing the agronomic efficiency of rock dust as a nutrient source in agriculture. *Rev. Cienc. Agron.* **2025**, *56*, 1–13. [\[CrossRef\]](#)
69. Oliveira, C.F.; Mendes, L.W.; Alleoni, L.R.F. Potassium organomineral fertilizer alters the microbiome of a sandy loam tropical soil. *Appl. Soil Ecol.* **2025**, *207*, 105960. [\[CrossRef\]](#)
70. Oliveira, C.F.; Trovato, G.H.C.M.; Fonseca, A.H.H.; Mota, L.H.C.; Santos, E.F. Phosphorus use efficiency in millet plants inoculated with entomopathogenic fungi. *J. Plant Growth Regul.* **2025**, *44*, 5471–5482. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.