HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

(MATE)

Challenges in Phosphorus Recycling and the Agronomic Efficiency of Bio-Based Fertilizers as Alternative Phosphorus Sources

The Thesis of the Ph.D. dissertation

Ari Kurniawati

Georgikon Campus

2026

The PhD School

Name	: Doctoral School of Natural Sciences
Discipline	: Environmental Sciences
Head	: Dr. Erika Csákiné Michéli, MHAS Professor, D.Sc. MATE, Institute of Environmental Sciences
Supervisor(s)	: Dr. Zoltan Toth Associate Professor, PhD MATE, Institute of Agronomy Dr. Gergely Toth Professor Joint Research Center of the European Commission Institute for Soil Sciences, Agricultural Research Center

....

Approval of the Head of Doctoral School

....

Approval of the Supervisor

....

Approval of the Co-Supervisor

Table of Contents

1 SHORT INTRODUCTION AND OBJECTIVES

1.1. Global crisis threatens fertilizer manufacture

The rising demand for food is still becoming a global challenge to the world since the increase of world population expected to reach 9.7 billion by 2050 (Randive et al., 2021). On the other hand, the world crisis leads to the inflation of energy, such as oil and gas. Therefore, the use of alternative sources for food production should be focused to maintain the stability of food availability.

Agriculture sector has a crucial role in achieving food security. However, its activity often contirbutes to high energy use. Energy and environmental issues in agricultural industry can be put together in one main topic, fertilizer. Fertilizer is becoming more crucial since the use efficiency of conventional fertilizer is threatened by the limited source of raw materials and environmental issues (Randive et al., 2021) along with the use of energy in producing the fertilizers.

Furthermore, global society faces serious phosphorus scarcity due to its essentiality, unequal global distribution, and, at the same time, regional excess of phosphorus (P) which could cause geopolitical problems, comparable to the geopolitical tension around fossil energy dependency (van Dijk et al., 2016). This condition affects market competition of conventional fertilizers, disrupting the stability of fertilizer supply.

1.2. The urgency of bio-based fertilizers to reduce dependence upon conventional fertilizer

Bio-based products are emerging due to the global pressure to convert wastes to nutrient-rich products that can be valorised in the agricultural sector (Vaneeckhaute, 2021). Potential nutrient-rich sources can be agricultural waste, food waste, wastewater, and sewage sludge, which are processed by specific technology for mineralization and are currently unused. Moreover, the availability of the raw materials for BBFs production is also abundant. In 2017, the EU-28 (28 EU Member States) generated 86 million tonnes of biowaste or 34% of municipal solid waste (European Environment Agency, 2020) in which unmanaged waste can cause serious environmental and health problems. In developing countries, the situation is even worst; the main food waste streams come from food market activities/areas, where it is usual to have a high production and a non-efficient waste management (Jara-Samaniego et al., 2017).

1.3. Bio-based fertilizers in supporting circular economy

The concept of BBFs is to support the circular economy (CE), proposed by the European Commission (EC) as the official EU strategy in 2014 (COM/2014/398 final). The EU target is to replace up to 30% of chemical fertilizers using BBFs (The European Commission, 2016). The government generates the strategy, policy, and law to support the implementation of BBFs, such as regulation (EU) 2019/1009 of the European Parliament and of the Council about

EU fertilising products (The European Union, 2019). Other than government policies, BBFs' production is also supported by non-governmental initiatives such as "waste-to-product" (Kaszycki et al., 2021; Preisner et al., 2022; Santagata et al., 2021), which is not only suggested by the EC but also by European Industrial Organization of Fertilizers (Chojnacka et al., 2020) and European Sustainable Phosphorus Platform (ESPP) (Smol, 2021).

Nowadays, BBFs' implementation is yet to reach the level of productivity of chemical fertilizers. Some of the challenges are the cost of transportation, technology process, regulation and certification, field validation trial, and social acceptance. Regarding farmers' responses, they are concerned about the mineralization process and hygienization of the products, and they expect a reasonable price than chemical fertilizers (Tur-Cardona et al., 2018). Despite many challenges, BBFs can support energy and materials recovery as a response to environmental and social problems (Chojnacka et al., 2020). To reach the objective, laws and policies that regulate BBFs' implementation should be developed precisely based on an assessment of impacts since BBFs are eco-friendly fertilizers to complement the existence of chemical fertilizers in terms of preserving the environment and productivity.

1.4. Objectives

This research aimed to study the agronomic efficiency of phosphorus in bio-based fertilizers and their potential as alternative energy sources to replace mineral P fertilizer as well as to investigate the impacts on circular economy in the current policies and regulations.

The objectives are as follows:

a) Determine the effect of bio-based fertilizers on phosphorus content and its availability in the loamy sand acidic soil and P uptake of the plants (direct and residual effects).
b) Determine the agronomic efficiency of bio-based fertilizers as P source for plants in the loamy sand acidic soil cultivated organically in Hungary.
c) Understand the current situation of bio-based fertilizers in replacing conventional fertilizers to support circular economy.
d) Study the current policies and regulations and other initiatives related to the utilization of bio-based fertilizers in technology and socio-economic aspects.

2 MATERIALS AND METHODS

2.1 Methods for field experiment

Long-term P bioavailability was studied with field trial and 8 types of BBFs to be tested. The field experiment was conducted with different crop rotations. To determine the direct effect of BBFs could be seen in the first year of maize cultivation, then the residual effects of BBFs could be seen in the second year of winter wheat cultivation. This research was going on under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 818309 (LEX4BIO), so all the methods referred to the field protocol for field trials within WP3 of the H2020 project LEX4BIO, with some adjustments based on the local conditions.

2.1.1. Experimental sites and weather conditions

A field experiment was established in Nikla, Hungary from May 2022 to July 2023. The first-year experiment was conducted from May to October 2022 and the second-year experiment was conducted from November 2022 to July 2023. As the P fertilization of crops was the focus, the experimental field with a low plant available P content was chosen to show effects of BBF treatments on the yield. The soil texture was loamy sand with 28 mg/kg Olsen P or 33 mg/kg based on ammonium-lactate soluble P method.

Climate norms were acquired from average of 1901-2000. The long-term mean annual temperature and total precipitation were 10.5 °C and 683 mm, respectively. During the experimental years (2022 and 2023), the monthly mean temperature and monthly total precipitation are presented in Figure 1. The low precipitation observed in July 2022, coinciding with the ear initiation and tasseling stages of maize, critically affected plant physiological processes and yield formation, as this growth stage is highly sensitive to water and nutrient availability for reproduction.

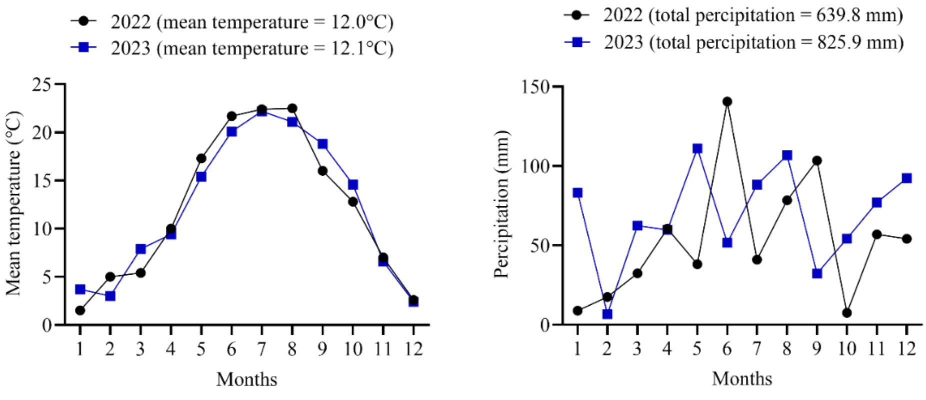

Figure 1. Weather data from Keszthely agrometeorological research station, Hungary (around 41 km far away from the experimental site).

2.1.2. Soil collection and characterization

Soil from field experiment sites were collected from the top 0 to 20 cm before the application of any fertilizers and after harvesting for each year. After collection, soils were air-dried and sieved to 2 mm and thoroughly homogenised. A representative subsample was characterized as described in Table 1.

Soil texture was analysed using sedimentation analysis or by the pipette method. Soil pH was determined both in H_2O and in 0.01 M $CaCl_2$ suspensions. Soil organic C (SOC) was calculated as the difference between total C and C originating from $CaCO_3$, which was considered to be equal to total C for non-calcareous soils.

Table 1. Parameters determined in soils

Parameter	**Note**
Soil type	Cambisol
Clay content	2 %
Silt content	22 %
Sand content	76 %
pH in $CaCl_2$	4.7
pH in H_2O	5.1
Soil organic carbon	0.6 g/kg

2.1.3. Crop and soil management

The experiment was started by soil preparation, treatments application, seedling, sampling, and harvesting (Table 2). Soil cultivation was done by preparing 36 m^2 plot area (gross) per treatment for maize cultivation in the first year. The plots were split in the second year for the determination of the residual effect on one half of the plot and a second application of BBFs and TSP (equal amount as in previous year) on the other half.

Table 2. Experimental timeline and activities

Period	Task	Note
Pre-planting 1 (April 2022)	Soil tillage and seedbed preparation	Soil was ploughed using harrow, planer, and basket harrow.
Planting 1 (May 2022)	Treatment application was done before seedling	Fertilizers were broadcasted on the soil surface before sowing and incorporated into the topsoil by ploughing or harrowing shortly after application.

Period	Task	Note
Destructive plant sampling (July 2022)	Observation of plant height, number of leaves, stem diameter, and leaf area of maize.	Observation was done at the elongation stage.
Plant harvesting 1 (October 2022)	Plant and soil samples were collected. The applied methods are detailed below (section 3.1.7).	Loss yields due to environmental factors.
Pre-planting 2 (November 2022)	Plot adjustment and fertilizer treatments application	The plots were split and only half were fertilized.
Planting 2 (November 2022)	Winter wheat sowing	Winter wheat was sown using a cereal grain seeder built on a disk tiller (Horsch Pronto).
Plant harvesting 2 (July 2023)	Harvesting of winter wheat	Winter wheat was harvested for yield and sampling data, together with soil sampling on the next day.

There was no irrigation during the planting period, also no chemical pesticide was done due to ecological farming system. The challenge that arisen was weed infestation managed by mechanical weed control. This condition was exacerbated by drought damage and fungal diseases in the first year causing the yield loss of maize. On the other hand, the next year's plantation resulted in better growing conditions. Also, the cultivar of winter wheat used (Chameleon) performed with strong resistance to diseases, and it has a unique balance of high yield, early maturity, and strong winter hardiness.

2.1.4. Experimental design and layout of the trial

The design of the first-year experiment was a Randomized Complete Block Design (RCBD) laid out in non-factorial arrangement. The total treatments were 13 divided by 8 types of bio-based fertilizers, 4 doses of TSP (25%, 50%, 100%, and 200% of standard P dose), and 1 control treatment without any fertilizers. Each treatment was replicated 4, so there were 52 plots in total.

For the second-year experiment, a separate analysis was performed for the residual and the fertilized subplots, which were affected both by the residual effect of the fertilization in the previous year as well as the freshly applied fertilization. Alternatively, a row column design with following model can be used:

$$y_{ijkl} = \mu + block_i + row_j + column_k + treatment_l + \varepsilon_{ijkl}$$

where μ is intercept; $block_i$, row_j, and $column_k$ are random effects of replication (=blocking factor), row within replication, and column within replication, respectively; $treatment_l$ is the fixed effect of treatment and ε_{ijkl} is residual error.

2.1.5. Fertilization treatments

To ensure that P is the only growth limiting nutrient, all other nutrients, especially nitrogen (N) and potassium (K) were supplemented in sufficient high and equal amounts in all treatments. Since the field is pure organic or ecological farming, N and K nutrients were coming from Vinasz (molasses fermentation residue) containing 80 kg N, 0.8 kg P, and 132 kg K based on 2000 kg ha^{-1} of fertilizer dose. The standard rate of phosphorus used was 30 kg P/ha based on the field protocol of the project. The detail of calculation can be seen in Table 3. An additional potassium nitrate (40 kg N/Ha and 135 kg K_2O/Ha) was also top-dressed into the area to enhance the amount of nutrients in the soil.

Table 3. The dose of phosphorus fertilizer treatments in the two years experiment

Treatments	1st year experiment Rate kg/plot (36 m^2)	2nd year experiment Rate kg/subplot (18 m^2)	
	Fertilized	Fertilized	Unfertilized
1. Control	0.00	0.00	-
2. TSP* 25%	0.15	0.08	-
3. TSP* 50%	0.31	0.16	-
4. TSP* 100%	0.62	0.31	-
5. TSP* 200%	1.23	0.62	-
6. Bioagenasol	8.78	4.39	-
7. Monterra 2-14-4	1.75	0.88	-
8. Meat&bone meal	1.73	0.87	-
9. Struvite	0.87	0.44	-
10. AshDec	1.30	0.65	-
11. Optisol Universal	6.10	3.05	-
12. EcoPlant-humi	5.71	2.86	-
13. Poultry litter ash	2.24	1.12	-

*TSP: Triple Superphosphate (40% P_2O_5; 17,44% P)

Since BBFs studied is to determine their predominance as substitutes for mineral P fertilizers, all BBFs tested should be commercially available on European or regional/national markets (Fig. 2 and Table 4). They were available across Europe at the time the experiments were conducted as pellets, granules, and powder, and taken from a list of 39 (Wester-Larsen et al., 2022) as well as selected based on source materials and processing technology. Another selection criteria were that they had a high technology readiness level and were available sufficiently large quantities in Europe, so it could be easily transported (Bauerle et al., 2021).

Figure 2. Different types of bio-based fertilizers were used in the field experiment.

Table 4. List of P-BBFs tested in the field experiments

Acronym	Year	Fertilizer Name	Description	PFC	CMC	P [g kg^{-1} FW]	P_2O_5 [g kg^{-1} FW]	C [%]	DM [%]
BA1	1&2	Bioagenasol	vegetable origin (wheat and maize fermented and distilled)	1 A-I	4/6	12.3	28.2	47.9	90.4
MO14	1&2	Monterra 2-14-4	vegetable by-products from food industry and animal proteins	1 A-I	6/10	61.8	141.8	23.8	91.7
MB1	1&2	Meat&bone meal (Biorga Vianos)	meat & bone meal	1 A-I	10	61.5	141.1	36.2	97.1
CGO	1&2	Struvite (Crystal Green)	struvite	1 C-I	12	124.7	286.0	0.4	54.8
ADC	1&2	AshDec	calcined phosphate from sewage sludge ash	1 C-I	13	80.5	184.5	0.1	99.9
OPU	1&2	Hühnermist (Optisol Universal)	chicken manure pellets	1 A-I	10	16.1	36.9	37.2	82.3
EPH	1&2	EcoPlant-humi	sunflower husk ash	1 C-I	13	18.9	43.4	5.8	97.1
PLA	1&2	Poultry litter ash	poultry litter ash	1 C-I	13	48.2	110.5	0.6	92.1

1 A-1 : solid organic fertilizers: ≥ 15% C organic
1 C-1 : solid inorganic macronutrients fertilizers
CMC 4 : fresh crop digestate
CMC 6 : food industry by-products
CMC 10 : derived products within the meaning of Animal By-products Regulation
CMC 12 : precipitated phosphate salts and derivates
CMC 13 : thermal oxidation materials and derivates

2.1.6. Harvest of field experiment

Plant was harvested by plot harvester machine. On the representative and defined harvest area, plants were cut at the soil surface to obtain total above ground fresh weight. Above ground parts were further separated into harvestable yields and remaining above ground parts. However, due to drought damage and fungal pathogen in the first-year experiment, there was no representative yield that can be recorded. The representative subsamples were taken and weighed for dry matter determination and for analysis. After 72 h drying (at max. 65°C), the dry biomass of all parts was weighed and then properly stored (in a tightly sealed bag at room temperature (<=20°C).

2.1.7. Data gathering and calculations

Destructive sampling was conducted during the first-year experiment to assess maize growth at 6 - 7 weeks after sowing. This stage is the beginning of a rapid growth phase or the elongation stage when the plant reaches 8 to 10 leaves. The parameters observed were plant height, number of leaves, stem diameter, and leaf area per plant. The detailed of the method used is performed on Table 5.

Table 5. Parameters determined at vegetative stage of maize plantation (first-year experiment)

Parameter	Unit	Method
Plant height per plant	[cm]	Plant height was measured from the soil surface to the highest leaf tip using measuring tape.
Number of leaves per plant		Number of leaves was counted manually per plant.
Stem diameter per plant	[cm]	The circumference of the plant was measured at one-third of its height using a measuring tape. Then, the number was converted to diameter using the calculation: circumference/π.
Leaf area per plant	[m^2]	Leaf Area (LA) was estimated using the constanta method at the seventh leaf = Length × width × 0.75. The factor of 0.75 is a general coefficient for maize. Then, the total leaf area per plant can be calculated by multiplying the sum of leaf numbers by the area of the seventh leaf.

In both years of field experiments, the parameters listed in Table 6 were determined. Biomass samples were milled and analysed for N and P concentration. At each harvest, soil samples were also taken from each plot of the field experiment (i.e. one composite soil sample containing 10 soil cores each) for P analysis.

Tabel 6. Parameters determined at harvest field experiments

Parameter	Unit	Method
Shoot biomass (fresh and dry matter), split into harvestable yield and vegetative parts	[g]	Weighing
N concentration in shoots (yield product and vegetative parts)	[%]	CN analyser (dry combustion or Dumas method)
P concentration in shoots (yield product and vegetative parts)	[g kg^{-1} dry matter]	Wet digestion with concentrated HNO_3 (determination of P was done through colorimetry using the molybdate blue method)
P content in the soil	[mg P kg^{-1} soil]	The bicarbonate-extractable P (Olsen P) method

To calculate the apparent P use efficiency (aPUE), the formulation used can be written as follows:

$$aPUE\ [\%] = \frac{P\ uptake_{BBF} - P\ uptake_{Pref0}}{P_{added}} \times 100$$

where $P\ uptake_{BBF}$ refers to P uptake in total plant dry matter in treatments fertilized with BBF while $P\ uptake_{Pref0}$ refers to the control treatment without any P addition. The total uptake of P was calculated as the sum of dry matter of the harvestable grain and vegetative plant parts, each multiplied by their respective P concentration. P_{added} is the amount of P (not P_2O_5) added with the fertilizers. In the second year of the field experiment, each plot was split into two subplots, one of them receiving a second fertilizer addition while the other subplot was used to investigate the residual fertilizer effect. Thus, in the second year, P added refers to the amount of P added in the respective year for the fertilized subplots and to the P amount added in the previous year for the residual subplots. All numbers given in kg P ha^{-1} for the field experiments.

The mineral replacement value (MRV), indicating the relative effectiveness of the organic fertilizers compared to the conventional fertilizer reference was determined as:

$$MRV\ [\%] = \frac{P\ uptake_{BBF} - P\ uptake_{Pref0}}{P\ uptake_{Pref100} - P\ uptake_{Pref0}} \times 100$$

with $P\ uptake_{Pref100}$ indicating the P uptake in the reference treatment fertilised with the standard rate of P as TSP.

P harvest index = P uptake (harvested products) / total P uptake

2.1.8. Statistical analysis

The data were analyzed using analysis of variance (ANOVA) in a factorial experiment on randomized complete block design (RCBD). Significant differences among treatment means were determined through Tukey Test ($p < 0.05$).

First, all the data were analysed separately per year and subplot. Considering the randomised complete block design of the individual trials, fertilizer treatment was considered as fixed effect, while block was introduced as random factor. For the second year, a separate analysis was performed for the residual and the fertilized subplots.

In a second step, due to the large data variability in the field experiments, determining meaningful estimates for MRV and aPUE was difficult and often resulted in negative values, where yield and P uptake were similar or even higher in the unfertilized control compared to the fertilized treatment. Therefore, data for these indicators was not analysed statistically.

2.2 Study overview of bio-based fertilizer characteristics and the challenges in implementation to replacing conventional fertilizers

To complement the methodological description of the field experiment, the following literature review provides a broader scientific context that supports the interpretation of the experimental findings. The desk study then continues by examining the characteristics of bio-based fertilizers and the challenges associated with their implementation as potential replacements for conventional fertilizers in the future. By integrating the experimental outcomes with established theories and comparable studies, the review strengthens the analytical foundation of this research and supports the development of informed recommendations for the future utilization of BBFs.

3 RESULTS AND DISCUSSION

3.1 Agronomic Efficiency of Bio-Based Fertilizers as Alternative Phosphorus Source for Plants

3.1.1 Growth and yield responses of maize to bio-based fertilizers in year one

Maize growth progressed well during the early stages of the season, as temperature and precipitation were adequate for crop establishment and vegetative development. However, during weeks 9 to 12 (July 2022), corresponding to the tasseling period, precipitation declined markedly, impairing the growth process. Because the field relied solely on rainfall, water management became a major challenge throughout the experiment. Following this dry period, weed infestation further exacerbated stress by competing for nutrients and serving as a host for fungal pathogens that affected the maize crop (Fig. 3). Mechanical weed control was not as effective as herbicide application at a larger scale. These combined constraints resulted in substantial yield loss; therefore, yield data could not be collected.

Figure 3. Weed infestation observed in the maize field before mechanical control

In the first plant sampling, the data showed no significant difference between treatments. However, there was a positive curve P response from conventional fertilizer where 30 kg ha^{-1} of P from TSP showed the best result on plant height, leaf number, stem diameter, and total leaf area per plant of maize (Table 7). Several BBF treatments (ADC, OPU, MB1, PLA, and EPH) performed comparably to TSP_100%, highlighting their potential as effective growth-enhancing inputs. Among all BBFs, MO14 exhibited the lowest values for every measured parameter.

Table 7. Effects of bio-based fertilizers to plant height, leaf number, stem diameter, and total leaf area per plant of maize at Nikla, Hungary, in the first experiment year (2022)

Treatment	Plant height per plant (cm)	Number of leaves per plant	Stem diameter per plant (cm)	Total leaf area per plant (m^2)
TSP_0%	161.64 ± 17.27	10.08 ± 0.56	1.82 ± 0.10	0.52 ± 0.11
TSP_25%	166.46 ± 10.58	10.17 ± 0.59	1.86 ± 0.12	0.58 ± 0.12
TSP_50%	171.98 ± 16.09	10.37 ± 1.01	1.88 ± 0.16	0.58 ± 0.16
TSP_100%	182.80 ± 14.12	11.17 ± 0.99	1.95 ± 0.12	0.67 ± 014
TSP_200%	170.78 ± 15.16	10.12 ± 1.42	1.81 ± 0.18	0.51 ± 0.14
BA1	165.73 ± 19.99	10.45 ± 1.01	1.88 ± 0.18	0.57 ± 0.14
MO14	157.81 ± 12.26	10.06 ± 1.14	1.82 ± 0.17	0.50 ± 0.13
MB1	158.45 ± 18.47	10.50 ± 0.43	1.99 ± 0.13	0.62 ± 0.12
CGO	161.84 ± 24.41	10.68 ± 0.82	1.89 ± 0.19	0.58 ± 0.13
ADC	179.76 ± 24.30	10.58 ± 0.75	1.88 ± 0.10	0.56 ± 0.05
OPU	175.97 ± 18.32	10.36 ± 0.97	1.95 ± 0.11	0.61 ± 0.12
EPH	172.70 ± 19.37	10.06 ± 0.84	1.90 ± 0.12	0.57 ± 0.12
PLA	173.83 ± 29.19	10.27 ± 1.35	1.87 ± 0.12	0.58 ± 0.12

Data are presented as the mean ± standard deviation (STDEV, n = 4)

In contrast with the first plant sampling, P content in the soil after harvesting showed no curve P response. Even though there was no significant difference, almost similar values for all BBFs are close to the 100% P reference, except BA1 (Fig. 4).

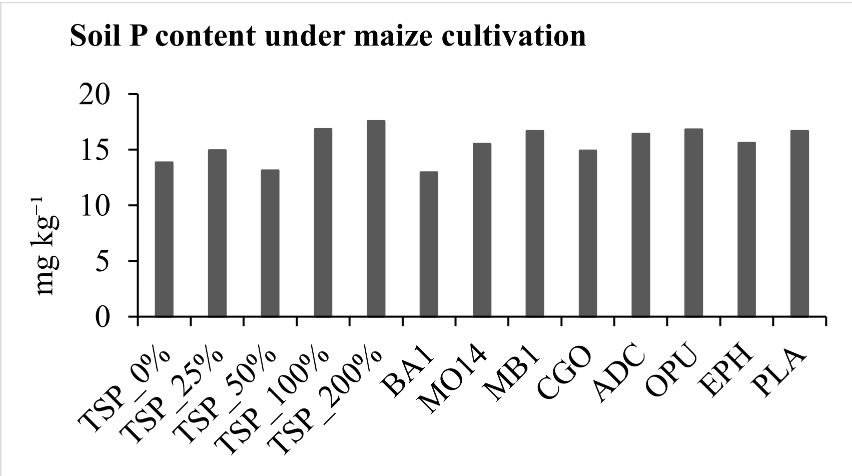

Figure 4. Effects of bio-based fertilizers on olsen P in maize fields at Nikla, Hungary, during the first experimental year (2022)

Although numerical variations in P uptake were observed among treatments (Fig. 5), the differences were not statistically significant ($p > 0.05$). Overall, MB1 produced the highest P uptake, surpassing both the control and all TSP treatments. Most other bio-based fertilizers exhibited comparable or lower phosphorus (P) uptake relative to the control. The TSP treatments demonstrated moderate P uptake, with no clear linear response to increasing rates, and TSP 200% resulted in reduced uptake.

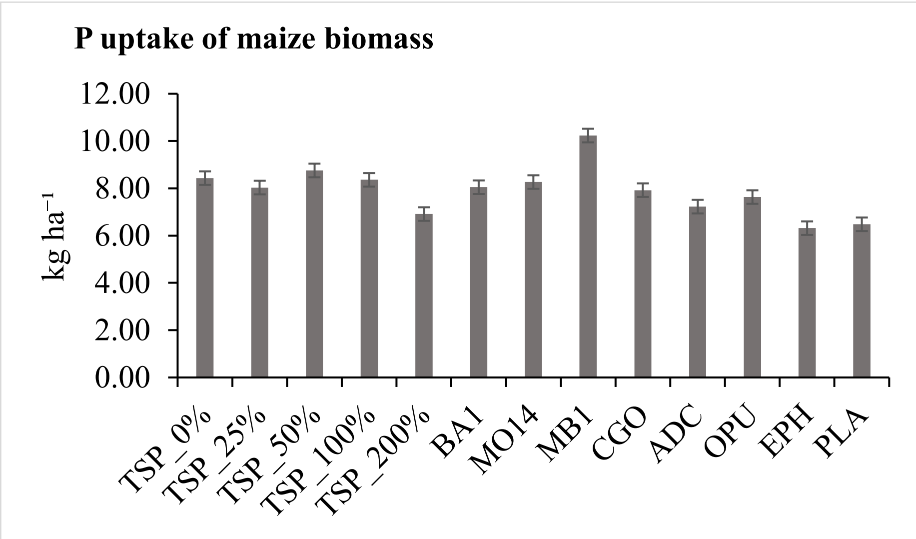

Figure 5. Effects of bio-based fertilizers on P uptake of maize biomass at Nikla, Hungary, during the first experimental year (2022)

The absence of statistically significant differences in P uptake among treatments may be attributed to multiple abiotic and biotic constraints experienced during the growing season. Prolonged drought conditions likely restricted root development and soil P diffusion, thereby limiting P acquisition by maize plants (Mahmood et al., 2025). In addition, severe weed infestation and disease pressure may have intensified competition for nutrients and impaired plant physiological functioning. Crop failure prevented grain yield assessment, which may have altered P partitioning and accumulation within plant tissues.

There is no consistent increase in N uptake from higher mineral P fertilization (TSP), but bio-based fertilizers show variable performance, with MB1 outperforming all treatments (Fig. 6). Meat bone meal (MB1) also resulted in higher stem diameter and leaf area (Table 7), which was consistent with its higher Olsen P levels (Fig. 4) and the greatest total P and N uptake by maize biomass (Figs. 5 and 6). This result in line with the findings of Stępień et al., (2021) that showed the increase of P concentration in the application of meat bone and meal due to high P in this organic source.

There was positive correlation observed between phosphorus (P) and nitrogen (N) uptake. Treatments that promoted higher P uptake, particularly MB1, also resulted in greater N uptake, indicating a synergistic interaction between these nutrients. In the study by (Wen et al., 2019), P fertilization from struvite significantly enhanced P availability and plant nutrient accumulation in calcareous soil, leading to improved uptake of multiple nutrients, such as N and Mg in vegetable crops

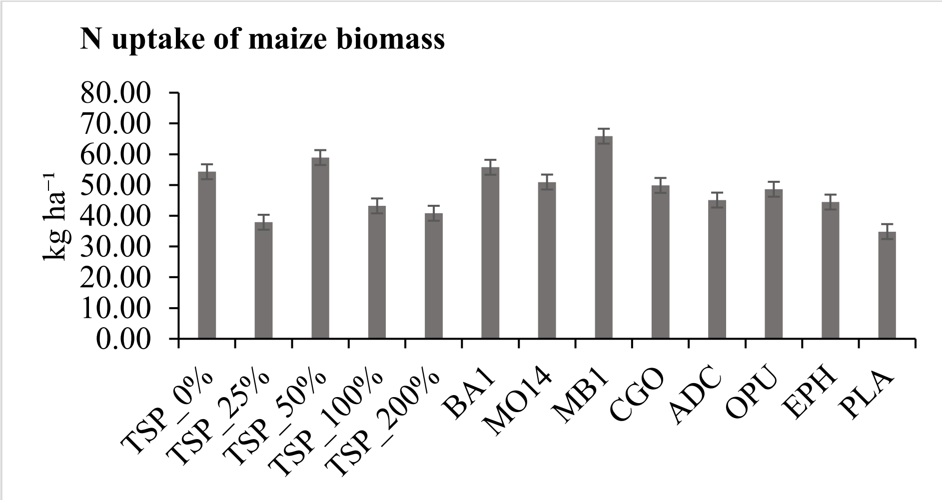

Figure 6. Effects of bio-based fertilizers on N uptake of maize biomass at Nikla, Hungary, during the first experimental year (2022)

3.1.2 Agronomic P efficiency of bio-based fertilizers for maize in year one

Apparent Phosphorus Use Efficiency (aPUE) reflects how efficiently plants use the applied phosphorus relative to the unfertilized control. Therefore, positive aPUE values indicate that the fertilizer improved the plant’s phosphorus uptake compared to the control, while negative aPUE values suggest that the fertilizer did not enhance P uptake and may have performed worse than the control.

Apparent phosphorus use efficiency (aPUE) varied substantially across treatments (Fig. 7). CGO and ADC exhibited the highest aPUE values (3.32% and 3.02%), indicating significant improvement in plant phosphorus uptake relative to the reference. Based on their characteristics, CGO (struvite) and ADC (calcined phosphate) have high P solubility, minimal soil fixation, and co-nutrient benefits, which together support efficient P acquisition by plants (Min et al., 2019; Nakagawa & Sarr, 2025). In contrast, the poorer-performing treatments likely contained P in less soluble forms or materials that interfered with plant uptake, resulting in lower or even negative aPUE values. According to Stępień et al. (2021), not all P is in soluble form and, thus, is not directly available for plants.

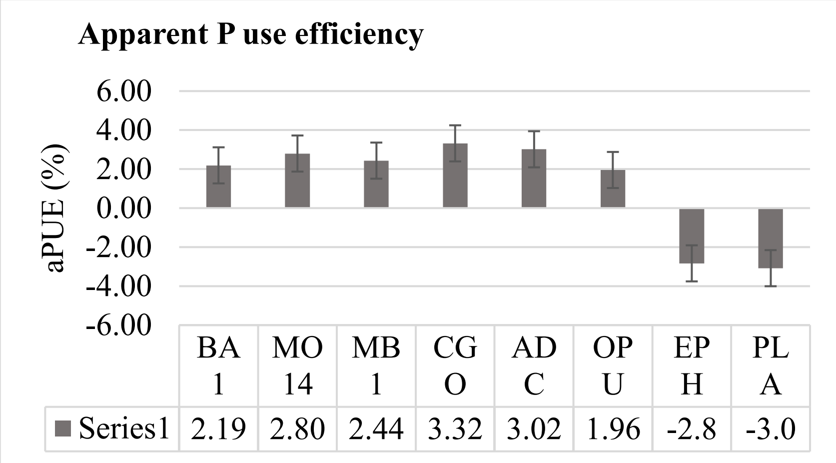

Figure 7. Apparent P use efficiency (aPUE) of bio-based fertilizers at Nikla, Hungary, during the first experimental year (2022)

Mineral replacement values (MRV) also varied widely among the tested recycled P materials (Fig. 8). Similar with the result of aPUE, CGO achieved the highest MRV (63.8%), indicating that it can replace nearly two-thirds of the mineral P fertilizer without reducing plant P uptake. Similar results were reported by (Frick et al., 2025), who showed that struvite can replace mineral P fertilizers under a wide range of European pedoclimatic conditions, with mineral replacement values often close to or exceeding 100 %. Moreover, ADC and MO14 also performed well (MRV 58.0% and 53.8%, respectively), demonstrating substantial mineral fertilizer equivalence.

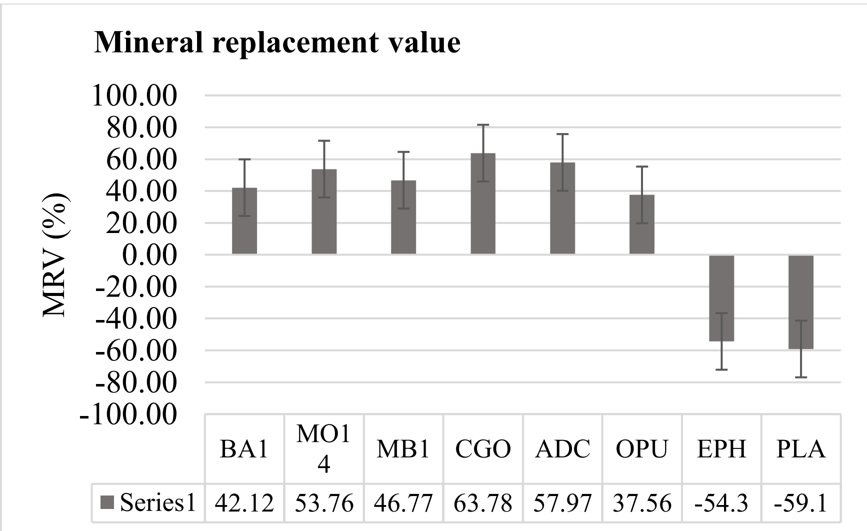

Figure 8. Mineral replacement value (MRV) of bio-based fertilizers at Nikla, Hungary, during the first experimental year (2022)

A strong positive correlation was observed between aPUE and MRV, indicating that treatments which enhanced P uptake relative to the control also showed the greatest mineral fertilizer substitution potential. Materials such as CGO and ADC displayed both high aPUE and high MRV, whereas EPH and PLA showed negative values for both parameters. This pattern is also consistent with the findings of Frick et al. (2025), who demonstrated that struvite-based bio-based fertilizers (CGO and ADC) can effectively replace conventional inorganic phosphorus fertilizers across diverse European pedoclimatic conditions, achieving high MRVs and stable crop responses.

In contrast, ash-based materials (EPH and PLA) showed lower and more variable agronomic effectiveness due to limited phosphorus solubility, which can restrict plant P uptake and result in poor fertilizer replacement performance. Phosphorus in biomass- and waste-derived ashes is commonly present in sparingly soluble forms, such as iron-associated or apatite-like compounds, resulting in low water solubility and limited plant availability (Kiani & Ylivainio, 2024).

3.1.3 Yield responses of winter wheat to residual effect of bio-based fertilizers in year two

A subsequent crop rotation with winter wheat was established shortly after maize harvest to evaluate the residual effects of the applied bio-based fertilizers. All straw generated within the experimental plots was retained in situ to maintain surface residue cover (Fig. 9). Overall, winter wheat exhibited better growth performance than maize; however, similar problems with weed infestation were observed due to the absence of chemical weed control. This constraint contributed to reduced winter wheat productivity, although under rainfed conditions the observed yield level was considered within a normal range.

Figure 9. Field preparation for winter wheat experiment in the second year.

The yield of winter wheat was around 3-4 tonnes per hectare under ecological farming. Although fertilized yields were generally higher than residual yields, differences among individual treatments within each category were not statistically significant (Fig. 10). Moderate TSP application (50–100%) and several bio-based fertilizers (MO14 and CGO) produced yields comparable to or higher than TSP 100% reference, indicating that certain bio-based sources can supply phosphorus effectively while also providing relatively strong residual benefits.

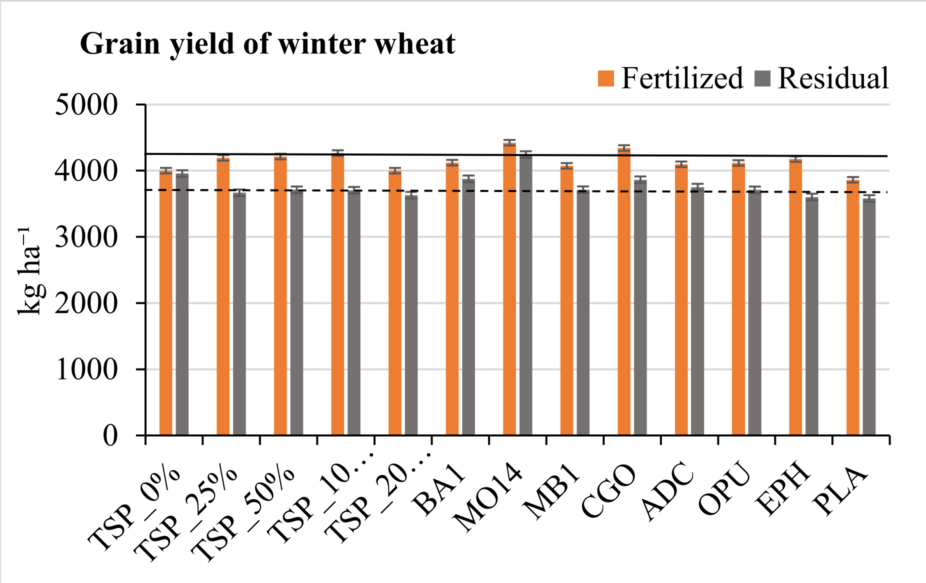

Figure 10. Grain yield of winter wheat (kg ha^{-1}) at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

There was a positive curve P response in conventional fertilizer, showing responsive results on fertilization (Table 8). Across fertilization treatments, grain phosphorus (P) concentrations ranged from 0.34–0.44%. PLA produced the highest P concentration (0.44%), significantly greater than MO14, which had the lowest value (0.34%). MO14 increased grain yield (Fig. 10) but resulted in a relatively low grain P concentration, likely due to a dilution effect where the larger grain biomass diluted the P content. Although MO14 supported strong plant growth, its slower P release meant that total P uptake did not increase proportionally to yield. Similar patterns have been observed with biobased phosphorus fertilizers, where strong crop growth did not always correspond to proportionally higher grain nutrient concentrations, even when total P input was comparable to conventional sources (Müller et al., 2024).

Table 8. Effect of bio-based fertilizers on grain phosphorus concentration of winter wheat at Nikla, Hungary, during the second experimental year (2023)

Fertilization treatment	P concentration (%)	Residual treatment	P concentration (%)
TSP_0%	0.35 ab ± 0.04	TSP_0%	0.33 ± 0.09
TSP_25%	0.37 ab ± 0.02	TSP_25%	0.40 ± 0.03
TSP_50%	0.39 ab ± 0.04	TSP_50%	0.37 ± 0.02
TSP_100%	0.40 ab ± 0.04	TSP_100%	0.40 ± 0.02
TSP_200%	0.39 ab ± 0.04	TSP_200%	0.38 ± 0.06
BA1	0.36 ab ±0.03	BA1	0.37 ± 0.01
MO14	0.34 b ± 0.03	MO14	0.35 ± 0.05
MB1	0.41 ab ± 0.02	MB1	0.38 ± 0.06
CGO	0.40 ab ± 0.04	CGO	0.40 ± 0.01
ADC	0.42 ab ± 0.06	ADC	0.34 ± 0.03
OPU	0.38 ab ± 0.03	OPU	0.39 ± 0.05
EPH	0.37 ab ± 0.05	EPH	0.37 ± 0.02
PLA	0.44 a ± 0.01	PLA	0.37 ± 0.05

Data are presented as the mean ± standard deviation (STDEV, n = 4)
Values followed by the different letter in the same column indicate significant difference between treatments based on Tukey's test ($p<0.05$)

Most bio-based fertilizers (BA1, MB1, CGO, ADC, OPU, EPH) yielded P concentrations comparable to mineral TSP treatments, indicating that they can supply P to the crop as effectively as conventional fertilizer. Residual P concentrations showed a similarly narrow range (0.33–0.40%) and followed patterns consistent with the fertilized treatments, suggesting that several bio-based fertilizers also provide sustained P availability in the second year, but not with residual treatment.

Figure 11 showed soil phosphorus (P) content (mg kg^{-1}) under fertilized and residual conditions across different fertilizer treatments. The P content in the soil was relatively small around 10 to 15 mg kg^{-1} compared to the initial P content in the soil which was 28 mg kg^{-1} due to the absorption of the plants. It was also indicating that treatments did not cause extreme accumulation or depletion of soil P.

Under fertilized conditions, several treatments (e.g., TSP 100%, MB1, OPU, ADC, PLA) showed slightly elevated soil P (around 11–13 mg kg^{-1}), reflecting higher P inputs or slower P removal. In contrast, treatments like MO14 and EPH showed the lowest soil P levels under fertilization (less than 10 mg kg^{-1}). Under residual conditions, soil P was generally slightly lower than the fertilized values but followed the same pattern for MB1 and PLA maintained higher residual P levels, while MO14 and OPU showed lower levels. This suggested that some treatments left more plant-available P in the soil after crop uptake, while others were associated with higher P use efficiency.

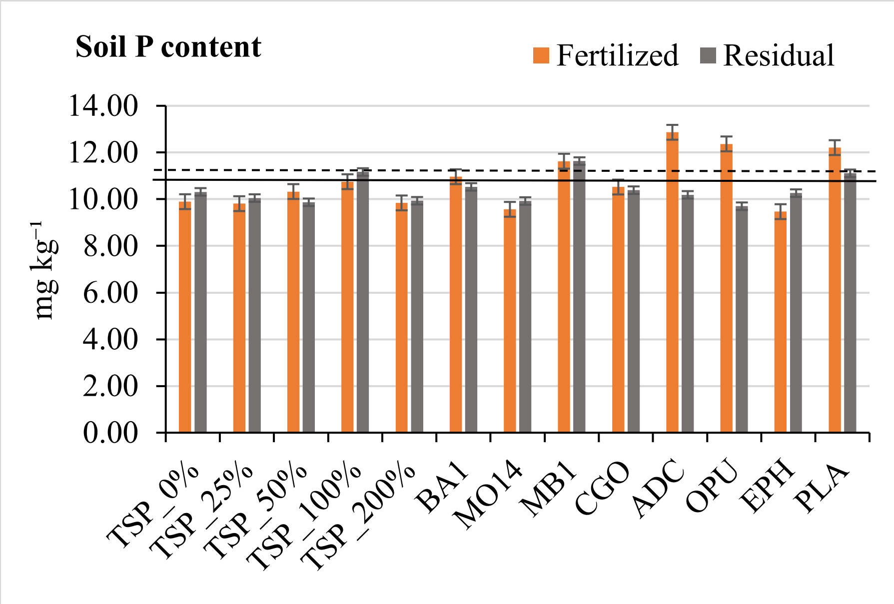

Figure 11. Soil P content (mg kg⁻¹) of winter wheat at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

Total phosphorus uptake of winter wheat varied numerically among phosphorus treatments, with values ranging approximately from 18 to 27 kg ha⁻¹ across fertilized and residual conditions (Fig. 12). The analysis of variance (ANOVA) indicated a significant overall effect of treatment on P uptake; however, Tukey's test revealed no statistically significant differences among individual treatments ($p > 0.05$). This indicates that although variability among treatment means existed, the magnitude of the differences between specific fertilizer sources was not sufficient to be distinguished at the selected confidence level. Uptake increased from the unfertilized control (TSP 0%) to the standard TSP 100% treatment, indicating a positive response to increasing P supply. However, a further increase to TSP 200% did not result in proportional gains in P uptake, suggesting diminishing returns at excessive P application rates.

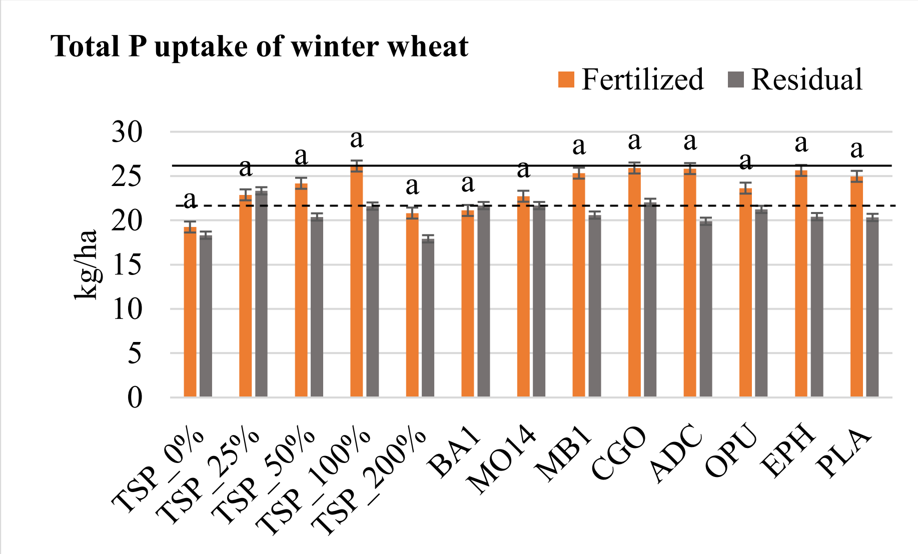

Figure 12. Total P uptake (kg ha⁻¹) of winter wheat at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

Grain yield and total P uptake responses showed contrasting patterns among fertilization treatments. Although MO14 produced one of the highest grain yields (Fig. 10), total P uptake did not increase proportionally and remained statistically comparable to other fertilized treatments (Fig. 12). The unchanged total P uptake strengthens a biomass dilution effect, whereby increased grain mass diluted P content rather than reflecting insufficient P supply. Müller et al. (2024) reported that commercially available biobased P sources can sustain crop growth and yield while producing variable effects on nutrient uptake and tissue concentrations compared with mineral references, reflecting differences in nutrient supply dynamics among fertilizer types, including slower or residual release patterns that decouple yield gains from proportional increases in P uptake or concentration in plant tissues.

All bio-based fertilizers produced P uptake values statistically comparable to the standard TSP rate (Fig. 12), demonstrating their equivalent effectiveness in supplying plant-available phosphorus under the conditions of this experiment. Across treatments, fertilized plots consistently showed higher numerical P uptake than residual plots, but these differences were also not statistically significant.

Total nitrogen uptake of winter wheat showed moderate numerical variation among phosphorus treatments, with values generally ranging from approximately 110 to 140 kg ha^{-1} across fertilized and residual conditions (Fig. 13). Uptake increased from the unfertilized control (TSP 0%) to the standard TSP 100% rate under fertilization treatments, indicating improved nitrogen acquisition with increasing phosphorus availability. Most bio-based fertilizers (MO14, MB1, ADC, and EPH) produced total N uptake values numerically comparable to those obtained with the standard TSP rate.

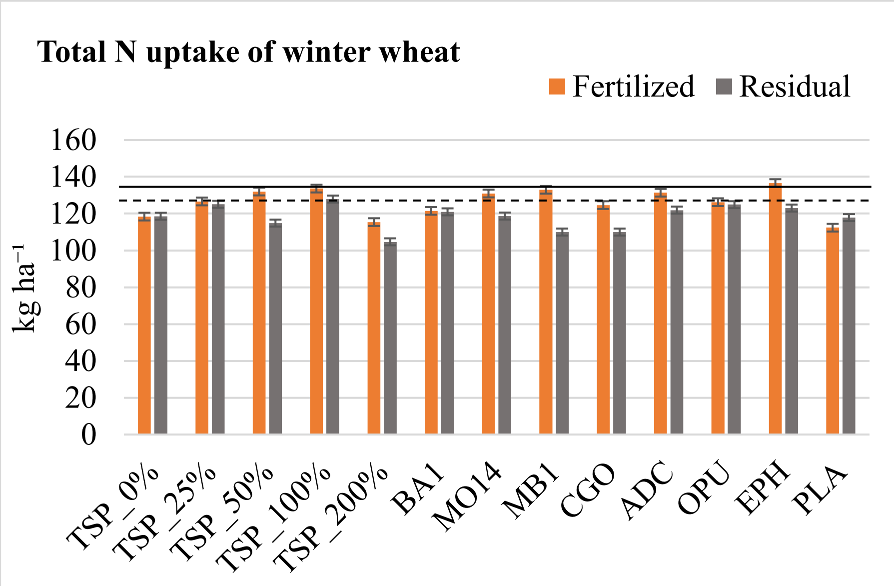

Figure 13. Total N uptake (kg ha^{-1}) of winter wheat at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

Grain nitrogen (N) concentration of winter wheat in the second year showed only small numerical variation among fertilization treatments and ranged from approximately 2.19 to 2.46% under fertilized conditions and from 2.16 to 2.51% under residual conditions (Table 9). Under fertilized treatments, EPH recorded the highest numerical grain N concentrations, exceeding TSP standard rate. Under residual treatment, the analysis of variance (ANOVA) indicated a significant overall effect of treatment on grain nitrogen concentration; however, all values were followed by the same statistical letter ("a"), indicating that no significant differences were detected among treatments by Tukey's test at the 5% probability level. This demonstrates that residual effects of all fertilizer sources resulted in statistically similar grain N concentrations.

Table 9. Effect of bio-based fertilizers on grain nitrogen concentration of winter wheat at Nikla, Hungary, during the second experimental year (2023)

Fertilization treatment	N concentration (%)	Residual treatment	N concentration (%)
TSP_0%	2.31 ± 0.22	TSP_0%	2.35 a ± 0.16
TSP_25%	2.24 ± 0.18	TSP_25%	2.36 a ± 0.23
TSP_50%	2.28 ± 0.10	TSP_50%	2.26 a ± 0.20
TSP_100%	2.40 ± 0.38	TSP_100%	2.51 a ± 0.14
TSP_200%	2.30 ± 0.14	TSP_200%	2.28 a ± 0.15
BA1	2.21 ± 0.31	BA1	2.37 a ± 0.19
MO14	2.19 ± 0.28	MO14	2.17 a ± 0.18
MB1	2.28 ± 0.25	MB1	2.29 a ± 0.13
CGO	2.20 ± 0.27	CGO	2.16 a ± 0.18
ADC	2.33 ± 0.27	ADC	2.19 a ± 0.24
OPU	2.23 ± 0.19	OPU	2.43 a ± 0.24
EPH	2.46 ± 0.18	EPH	2.35 a ± 0.13
PLA	2.29 ± 0.09	PLA	2.27 a ± 0.07

Data are presented as the mean ± standard deviation (STDEV, n = 4)
Values followed by the same letter in the same column indicate no significant difference based on Tukey's test at the 5% significance level.

Overall, the results indicate that neither increasing mineral P rates nor application of different bio-based fertilizers had a significant effect on grain nitrogen concentration in the second year, and that all treatments maintained comparable grain N levels. This suggests that grain N concentration was relatively stable and largely independent of fertilizer source and residual phosphorus availability under the conditions of this study. A recent field study found that, when nitrogen was applied uniformly across treatments, grain N concentration was not influenced by the phosphorus fertilizer source. This reflects that under adequate N supply, differences in P source may not change grain N levels (Brye et al., 2024).

3.1.4 Agronomic P efficiency from residual effects of bio-based fertilizers for winter wheat in year two

The mineral replacement value (MRV) of the different bio-based fertilizers (BBFs) varied widely, indicating large differences in their ability to substitute for mineral phosphorus fertilizer. CGO and ADC recorded the highest MRV values (Fig. 14), both close to and slightly below 100%, demonstrating that these BBFs were nearly equivalent to mineral fertilizer in terms of phosphorus supply to the crop. EPH and MB1 also showed high MRV values (around 90% or above), indicating strong fertilizer replacement potential.

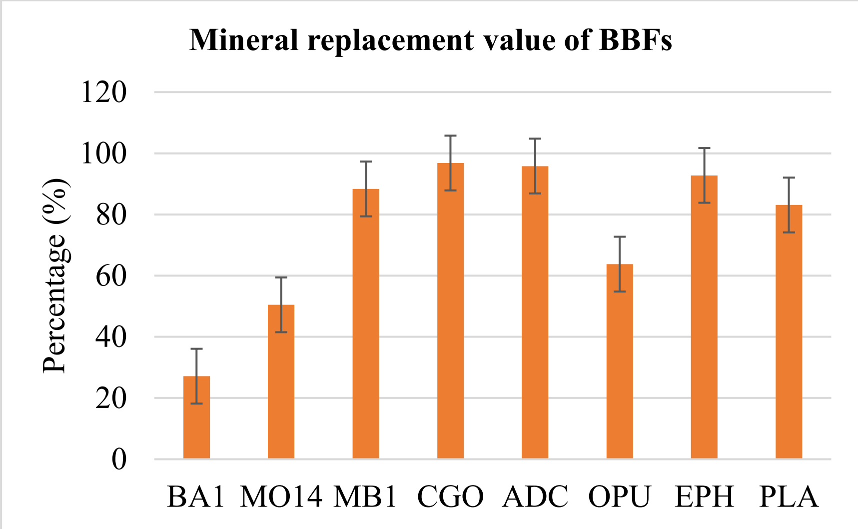

Figure 14. Mineral replacement values (MRV) of bio-based fertilizers (BBFs) for the fertilized subplot at Nikla, Hungary, during the second experimental year (2023).

The apparent phosphorus-use efficiency (aPUE) of the different bio-based fertilizers (BBFs) varied widely (Fig. 22), indicating substantial differences in their ability to supply plant-available phosphorus. Among the treatments, CGO and ADC recorded the highest apparent PUE values (about 22–23%), closely followed by EPH and MB1, which also exhibited high efficiencies exceeding 20%. This variation in aPUE among BBFs was closely reflected in their effects on the harvest index of winter wheat (see Fig. 15).

Fertilizers with the highest apparent PUE, particularly CGO and ADC, also produced harvest index values comparable to or slightly higher than the standard TSP 100% rate under both fertilized and residual conditions. This indicates that these sources not only supplied plant-available phosphorus efficiently but also supported effective partitioning of biomass into grain. However, this relationship was not strictly linear, as some BBFs with high aPUE exhibited reduced P harvest index.

The EPH treatment exhibited high apparent P use efficiency but comparatively low P harvest index, indicating efficient phosphorus uptake but limited translocation to grain. This suggests that post-uptake processes, including remobilization efficiency and sink strength during grain filling, constrained P allocation under this treatment. This aligns with findings from (El Mazlouzi et al., 2022), in wheat, a large proportion of grain P comes from remobilization of P stored in vegetative tissues, with post-anthesis uptake contributing relatively little directly to grain P. Moreover, environmental stress including weed infestation during the reproductive stage may have further exacerbated this decoupling between P uptake and grain P accumulation.

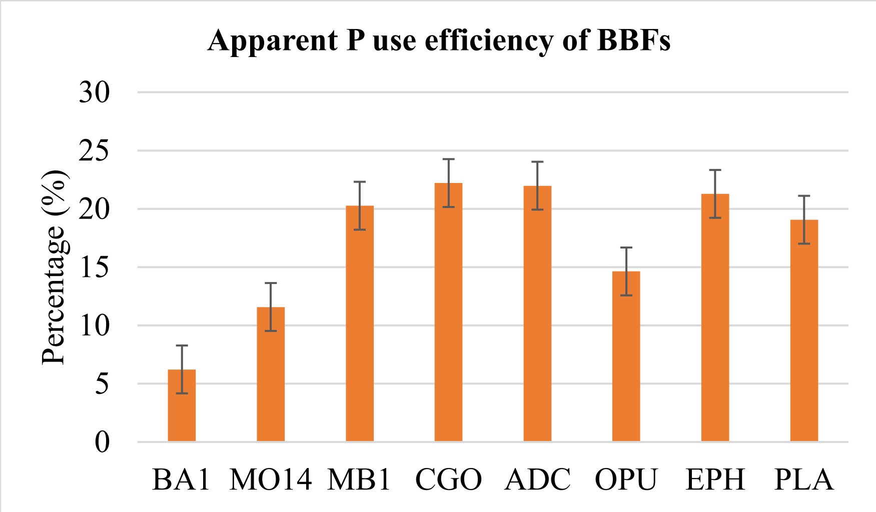

Figure 15. Apparent P use efficiency (aPUE) of the BBFs for the fertilized subplot at Nikla, Hungary, during the second experimental year (2023).

Overall, the harvest index of winter wheat varied moderately among the different phosphorus treatments, with values generally ranging between about 60 and 77% (Fig. 16). When compared with the standard phosphorus application rate of TSP 100%, most BBFs produced comparable harvest index values in winter wheat, indicating similar effectiveness in supporting biomass partitioning to grain. The small differences between fertilized and residual treatments across most fertilizer sources (including BA1, MO14, MB1, CGO, ADC, OPU, and PLA) indicate a strong residual P effect and high recovery efficiency of soil-stored phosphorus by winter wheat.

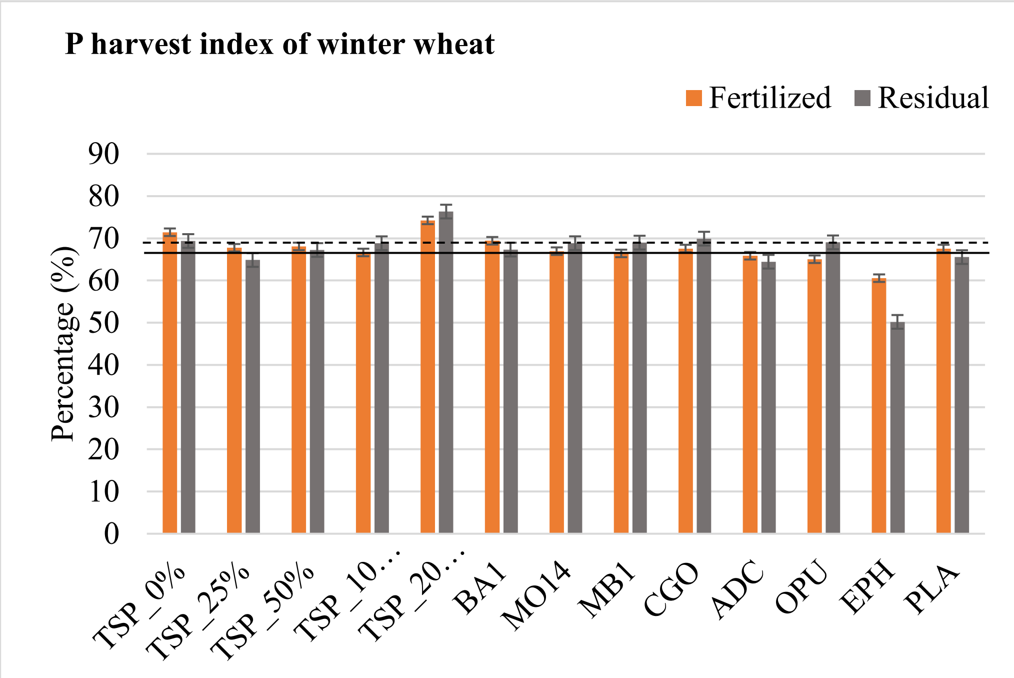

Figure 16. P harvest index (PHI) of winter wheat in the second year of the experiment. Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

3.2 An overview of bio-based fertilizer characteristics compared to commercial fertilizers

To be seen fairly, in terms of actual nutrient content, conventional fertilizer is more stable than that of BBFs to maintain the value of nutrient concentration because there is no biochemical process (unless proper analysis for each batch is available). Moreover, bio-waste products sometimes generate air pollution because they still leave the odor after processing, especially if there is contamination when it is not stored properly. Odor is mostly caused by the ammonia gas, and it also can cause element loss and reduce the quality of compost (Zhu et al., 2021). However, some additives can be used during composting process to reduce the odor emissions by providing porosity or absorbing gas. Also, potential NH_3 volatilization is also affected by soil types (such as acidic sandy soil) and the application method of fertilizers, while incorporation of BBFs was better to reduce the volatilization compared to surface application (Wester-Larsen et al., 2022). There are challenges in the level of field implementation between BBFs and commercial fertilizers.

Shifting from commercial mineral fertilizer to bio-based fertilizer is not about changing the fertilizer but more into the mindset since we are going to intervene in society. The use of conventional fertilizer has been ingrained with all the advantages. On the other hand, bio-based fertilizers are expected to partly or fully substitute for conventional fertilizers in the future. The challenges are a long-run process to achieve, but the starting is a key. The products should have similar characteristics to conventional fertilizers that farmers buy today, such as similar nutrient composition and content, having fast release of the nutrients, hygienic, and in solid form (Tur-Cardona et al., 2018). Low nutrient concentration causes voluminous quantity to use. Moreover, various forms of BBFs sometimes do not suit the characteristic of fertilizers spreader. These disadvantages are not beneficial in terms of transportation handling.

Transportation handling is also related to the transportation cost. Some of BBFs have been developed into granules which are easy to carry and store. Recovery and recycling of nutrients from chicken manure via granulated organic and organo-mineral fertilizer into added value fertilizers have to be intensified to accelerate the transition towards circular economy (Mažeika et al., 2021). However, the effect of high transportation costs remains for other types of BBFs because granulation or pelletization only can be applied in solid form of BBFs. Thus, the potential opportunities for developing BBFs are going to be enormous because the technology used requires improvements and more in-depth information.

The challenge of cost is not only in transportation but also in production. BBF production on a large scale will face high production costs, whereas the most vital consideration is the price since farmers' decisions mainly depend on the price for the adoption of BBFs in practice. The technology process related to BBFs production needs advanced and proper equipment, and it is taking more time to reach the break-even point after investments. Hou et al. (2018) reported that more information should be conveyed to technology users regarding aspects of a specific technology, i.e., financial viability, optimal operation conditions, regulations and incentives, and the agronomic and environmental performance of the technology.

In terms of costs, BBFs could be a double-edged knife since they can be a new business model and market opportunity, but they also can produce high-cost fertilizers compared to conventional fertilizers. However, on the wider side, BBFs could be cheaper or more expensive depending on the strengths of nutrient management, preserving the environment, and policy of circular economy. BBF is serving the world's needs to secure food production while maintaining ecosystems.

3.3 The analysis and evaluation of current implementation scenario to support bio-based fertilizers in replacing conventional fertilizers

EU Circular Economy Package introduces not only the new FPR regulation, but also the Farm-to-Fork Strategy which mitigates soil, air, and water pollution by increasing nutrient use efficiency (NUE) by reducing nutrient losses by 50% by 2030. Also, the new Common Agricultural Policies 2023-2027 which assign 25% of 1st pillar support payments to eco-schemes will be a key tool in reaching the ambitions of the Farm-to-Fork Strategy. These whole scenarios would be integrated to support the program linked and it can be used as a strong force in the development of BBFs and their application specifically. However, the implementation model approach of bio-based fertilizers could vary depending on the situation and condition at the farm level (see Table 10) and each model could serve different perspectives to comply with the new FPR to be adopted sustainably. A bio-based fertilizer with the same volume as a chemical one, with assurance about its nitrogen content, and at a lower price is preferred by most farmers (Tur-Cardona et al., 2018).

Table 10. Implementation model approach of bio-based fertilizers in EU

Contribution	Model of implementation	Challenges	Recommendations
Chojnacka et al., 2020	The use of biological waste to recover valuable fertilizer components	Logistic and production organization	Incentives for recovery of waste streams and fines for the use of non-renewable raw materials
Kaszycki et al., 2021	Polish sewage treatment using anaerobic digestion	The treatment of post-fermentation eutrophic sludge liquors requires additional costs	Granulated soil fertilizer production
Guilayn et al., 2019	Digestate could be used as bio-based fertilizer	Digestate (without any post-treatment) did not fulfil French standards and the latest European Union regulation proposal on fertilizers	Post-treatments and/or product formulation can be applied to meet the needs for organic fertilizers and soil improvers for digestates from source-separated AD inputs.

Contribution	Model of implementation	Challenges	Recommendations
Preisner et al., 2022	Circular economy indicators for resource recovery focused on technological aspects in the wastewater sector	Policy incentives to increase the recovery of nutrient-rich waste streams in wastewater treatment plants were not fully implemented in many countries.	The adoption of circular and sustainable practices for using waste by-products from the wastewater sector should be encouraged through circular economy indicators.
Silva et al., 2019	Biomass ash utilization in soil amelioration and nutrient recycling	The use of ash-based materials doesn't fully cover by the new FPR.	Two EU legislative frameworks: the WFD and the new FPR can support recycling of ash-based materials as soil fertilizers.
Santagata et al., 2021	Food waste recovery	Technological, economic, and cultural challenges	Adjustment on local condition is important to design and plan the recovery pathways
Smol, 2021	Nutrient-rich waste fertilizers (from water and wastewater)	Low level of experience from the end-user and low level of acceptance from social and health aspects	Frequently conducting dissemination activity of the waste-based fertilizer to the end-user while building social trust
Case et al., 2017	Processed and unprocessed organic waste-based fertilizers	Unpleasant odor produced by the fertilizer (social), uncertainty in nutrient content and difficult to use (technical)	Developing better manure processing for the bioenergy recovery, creating a model of producing fertilizer by the mixed involvement from government and industry to boost organic fertilizer availability.

Contribution	Model of implementation	Challenges	Recommendations
Hijbeek et al., 2019	There are four types of waste-based fertilizers tested in this study (straw incorporation, green manure or cover crops, compost, and farmyard manure)	Farmers found bacteria, parasites, or plant diseases after the application of organic fertilizers	Providing specific guidance on the best practice of using organic matters to prevent unwanted pests and diseases. Addressing more research on the financial consequences of using organic inputs both in short and long terms.
Kominko et al., 2021	Organo-conventional fertilizers manufacturing	Potential presence of pollutants, lack of consumer confidence, lack of support incentives, and difficulties related to waste status of input materials (sewage sludge and poultry ash)	Developing the quality of input materials to obtain 'safe' fertilizers

Source: author compilation, 2024

3.4 The implementation challenge of BBFs: technology and production aspects

Having 25% of EU agricultural land under organic farming is targeted by EU farm-to-fork strategy by 2030. However, the use of biobased fertilizers for organic farming is still under evaluation, while circular bio-based economy focusing on nutrient recovery and recycling. Several raw materials were not included in the new FPR, so public consultation is still ongoing to propose and review the legal act. For instance, through European Commission's Join Research Centre (JRC), a technical working group (STRUBIAS subgroup) proposed Struvites, Biochars, and Ashes as CMC 12 (Precipitated phosphate salts & derivates), CMC 13 (Thermal oxidation materials and derivates), and CMC 14 (Pyrolysis and gasification materials) that is already published as a scientific report (Huygens et al., 2019). In the case of biomass ashes, the maximum limit of organic carbon is still under discussion due to certain types of ashes containing high organic carbon but still delivering valuable macronutrients to the soil. Also, limits for contaminants such as chloride and organic pollutants are still unclear. The STRUBIAS report mentioned mere labelling "poor in chlorine" for PFC containing chloride concentrations lower than 3% wt (dry matter basis) (Silva et al., 2019).

Furthermore, the manufacturing chain of animal by-products (ABP) to be feed stock or fertilizer is still questionable to put on the market for human consumption since the use is under veterinary control or request from the European Food Safety Authority (EFSA). On the other hand, animal by-products including meat-and-bone meals (MBM) could have possibility to replace conventional fertilizer. The macronutrient concentration in the maize grains following the application of MBM was like the composition of the grains of maize fertilized with mineral N, P and K fertilizers (Stępień et al., 2021). Like conventional fertilizer, after considering the legal requirement in toxic content, the risk of contaminant in BBFs still exists due to exposure of heavy metal accumulation. Increased doses of organo-conventional fertilizer can lead to the accumulation of heavy metals, especially cadmium (Cd) and Nikel (Ni) in plant biomass, so it is recommended for biofuel production or ornamental plants since the risk that they enter the food chain is not studied yet (Kominko et al., 2022). The idea is to use ABP as fertilizer applied only for forest plantation, but the question: is it profitable to develop it on a large scale? Future research should address this issue. On the ground and the surface of water bodies, Liu et al. (2022) and Zhao et al. (2021), found out that $NiFe_2O_4$–g-C_3N_4 and CuO–g-C_3N_4 composite can be used for photocatalytic degradation of tetracycline hydrochloride antibiotic and for inactivation of *E. coli* bacteria.

Although the new law does not mention producing certain forms other than liquid and solid, the form of BBFs is also essential to be considered because it is connected to the logistical issue. Hence, the producer company has the challenge of shaping the BBFs into materials that are easy to carry and store as well to use by the farmers. For instance, in Poland, the eco-innovative approaches obtained novel granulated fertilizers from urban wastewater treatment and management of sewage sludges. However, extra cost is needed to manage the hazardous waste after fermentation (Kaszycki et al., 2021). Differently, Kominko et al. (2021) found that the developed method of organo-mineral fertilizer manufacturing does not include complicated technological operations, which would be associated with the increased cost of fertilizer manufacturing, but it is adapted to selected plants. Therefore, the situation and condition of BBF production vary from place to place. Santagata et al. (2021) suggested that the production process of waste by-products must carefully acknowledge local characteristics.

3.5 The implementation challenge of BBFs: socio-economic aspects

Regarding the socio-economic aspect, complexities in formulating and implementing policies related to BBFs were frequently present. Farmers are ready to accept BBF albeit asking for some requests (i.e. low-price guarantee, application guidelines, and detailed material content). On the other hand, policymakers also need to pay attention to the public acceptance of fertilizers and food products from waste-based materials. Although there are several goals to be achieved, the community is the important goal of this scheme due to its significance of accepting newly innovated products. In addition, if one of the EU's strategic agenda is circular economy, then the points related to pricing and product availability are highly recommended to be addressed in further policy discussion.

The policy addressing BBF implementation is expected to support the EU's circular economy and sustainability movement. The new FPR policy has incorporated those objectives in several important points as you can see from Fig. 17. The future policy could be improved by tackling its blind spots. There are two key stakeholders to be considered: producers and end users (farmers).

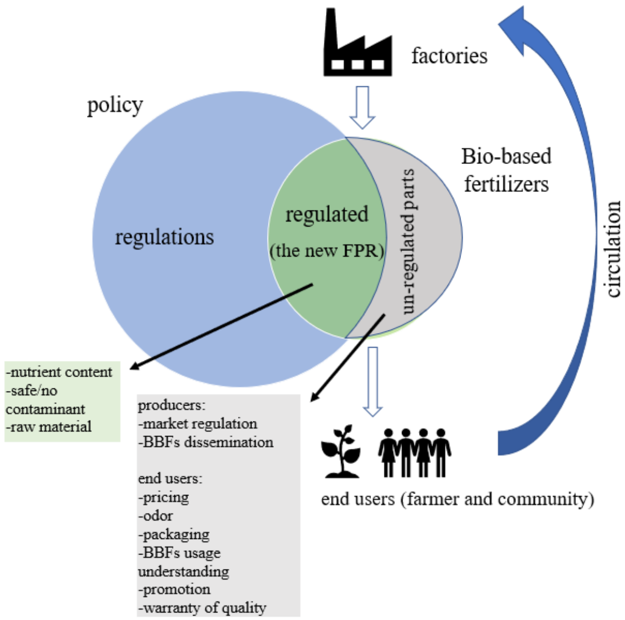

Figure 17. The new FPR in relation to the domains related to BBFs.

The policy demands clarity of nutrient content which must be stated through detailed information on the fertilizer packaging. This regulation can address one of the farmers' issues, in which they are hoping for detailed information regarding nutrient content to escalate their farming analysis (Hijbeek et al., 2019). Moreover, the new FPR policy has also encouraged manufacturers to provide application methods for specific products. Labelling on the PFC level is stated under the new FPR policy, which may help farmers minimize the risk of application failures (Huygens et al., 2019).

Even with this, the policy draft can be improved by considering other research findings related to BBF implementation in the EU. The BBF product can be further developed according to local characteristics. In this regard, several EU countries have different regulations and standards. For example, there is an obligatory policy for sewage sludge producers in France to be able to spread their waste on agricultural land (Lupton, 2017). Moreover, bio-based or waste-based fertilizers often need help in meeting regional standards. On the other hand, to meet health and environmental standards, the production process usually connects to specific technology, which involves additional costs often ignored when considering the economic framework of complex waste-utilizing systems (Kaszycki et al., 2021). Again, prices are prominent for business activity.

Previous studies from Case et al. (2017) and Tur-Cardona et al. (2018) show that farmers expect BBF to have competitive prices, even less than conventional fertilizers. However, no BBF-related policies have addressed the price or cost of making BBF. In this case, recommendations from policymakers will help find the right price that can benefit both parties, i.e. manufacturers, and end-users (farmers). A comfortable relationship between manufacturers and farmers could boost bio-based product implementation in the agricultural field (Case et al., 2017). Furthermore, some farmers sometimes question the price instead of ensuring the result after applying BBF products (Case et al., 2017; Hijbeek et al., 2019).

BBF-related policy, including the new FPR, must also increase the BBF dissemination function to stakeholders, including farmers and the public. In addition to farmers needing more experience in using BBF, the general acceptance of this product could be higher. There are negative public perceptions towards waste-based fertilizers (Kominko et al., 2021), such as bio-based fertilizers can cause unpleasant odors (Case et al., 2017) and uncertainty health impact (Smol, 2021). In this case, agricultural extension's participation in promoting BBF products can be paramount to reducing farmers' reluctance to use BBF. Moreover, government and manufacturers should boost their campaigns to increase BBF's social acceptance level while also securing any issue on the parameter of health. In the realization program, the European Commissions through their research and innovation has been doing the dissemination agenda (such as demonstration plots) and scientific publication as the results to show the effects of BBFs utilization for public (Directorate-General for Internal Market, 2022).

3.6 The implementation challenge of BBFs: socio-economic aspects

The EGD develops the feasibility of regulatory measures to improve the market for secondary raw materials with obligatory recycled content (Huygens et al., 2019). This situation is stated in some scenarios, such as Farm-To-Fork (F2F) Strategy, Biodiversity Strategy, Chemicals Strategy, Zero Pollution Action Plan, and Circular Economy Action Plan. EU F2F strategy directly impacts nutrients (fertilizer use), and it is required to use bio-based fertilizers to support EGD's implementation. Furthermore, the development of BBFs offers business opportunities for farmers and producer/supplier companies. For farmers, their land will be healthier in the long run due to organic input from fertilizers (Hijbeek et al., 2019). For companies, producing BBFs based on regulation standards is quite challenging. However, once it can be adopted, it can be developed around countries by slightly modifying the local plants and raw materials. Hence, the benefit of decentralization can be achieved step by step, plus its sustainability for all sectors involved.

Mostly, the challenges of BBFs implementation come from the technology process to produce fertilizers which are supposed to meet the rapid change in the global situation related to fertilizers, such as growing demand, energy issues, changing supply chains, and issues of logistics, limited sources, and environmental issues. In line with Davidson et al. (2015) that it will take further technological advances to generate more food with less pollution. However, it will also need regulations considering the social and economic aspects influencing farmers' choices. We need to develop partnerships among actors in the value chain, as described in Fig. 18. The conversion of waste into valuable items requires the fulfilment of several circumstances (quality of waste, condition of processing, law, and local conditions) (Kacprzak et al., 2022).

The circularity of BBF usage could support the goals and outcomes of a circular economy. However, the core application is highly complex because each production process could vary depending on raw materials. Hence, it would be formidable to set monitoring tools generally. For instance, in the wastewater industry, the designed indicators for resource recovery monitoring were the importance of the global or local circularity level, range of application, and appropriate units (Preisner et al., 2022). These indicators are needed to measure the circularity of BBFs usage and to propose a recommendation based on CE framework's development.

Figure 18. The role of Policies and Facilities to support stakeholders on BBFs implementation.

The existing regulation through the new FPR supports the partial replacement of conventional fertilizers by bio-based fertilizers while ensuring minimum nutrient losses. The nutrient use efficiency through increasing nutrient recycling and recovery of BBFs could be a way out of import dependency for fertilizers. To keep this mindset in farmers' minds, we need intense political and social pressure to adopt cutting-edge biobased technology promoting waste management practices that are economically advantageous and environmentally safe (Kaszycki et al., 2021). Moreover, Silva et al. (2019) also mentioned that adequate regulation for biomass ash as a raw material from the energy industry is acknowledged as the most important driving force for the adoption of proper ash management and valorization.

The characteristics of raw materials, such as origin, composition, and complexity induce difficulties to achieve an industrial scale fertilizer even to meet the current regulation. Bio-based fertilizer tends to be a local solution, so it opens opportunities for many sectors to develop BBFs based on available situation and condition, while the government also works on the legal facilities. Through study and research, the finding of specific treatment for specific raw materials helps producers build the plant quickly. For instance, in the case of anaerobic digestion residues, there is a tool suggested by (Guilayn et al., 2019) that raising the quality of digestate management and policymaking can be accomplished by using a digestate typology developed based on fertilizing value. Finally, facilitated product conversion along the following path results in economic and environmental circularity: environment of soil or water → bioorganic waste → treatment (biotransformation, biodegradation, mineralization) → fertilizer → soil or water (Kaszycki et al., 2021).

4 NEW SCIENTIFIC RESULTS

a. According to the field experiments on a central European Cambisol we found no significant difference between the agronomic effect of BBFs and the 30 kg P/ha dose of conventional P fertilizer.
b. Results from the case study of a central European Cambisol proved that BBFs can partially or fully replace commercial P fertilizer since it has similar direct and residual effect to conventional fertilizer in the same total P applied.
c. Results of the desk study on policies and regulations related to the implementation of bio-based fertilizers (BBFs) indicate that farmers' acceptance, compared to conventional fertilizers, largely depends on raw material availability, transportation logistics, nutrient content, production technology, and cost.
d. Several sectors, including the chemical industry, technology providers, waste-management bodies, and stakeholders, were identified as key contributors in ensuring safety, fostering evidence-based trust in the use of bio-based fertilizers, and supporting the development of an appropriate legislative framework. Furthermore, the findings highlight that society, particularly farmers, acts as the main driver of the circular economy in nutrient management.
e. The results of both field and desk study, supported by findings from similar studies reported in the literature, indicate that successful future adoption of bio-based fertilizers (BBFs) will require additional regulations tailored to the local conditions of each country, considering their geographical and socioeconomic characteristics. The analysis also revealed that regional initiatives may play an important role in addressing the limitations of current policy implementation.

5 LIST OF PUBLICATIONS

1. Agyemang ED., Molla GT., **Ari K.**, Andras T. 2021. Environmental problems associated with small-scale mining in Africa: Ghana's perspective. Georgikon Journal Vol 25(1): 2-17.

2. **Kurniawati A.**, Ratna DHW., Nur KW., Zoltan T., Gergely T. 2021. Alternative of Circular Biobioeconomy in Organic Farming Under Excessive Nutrients (Goat manure and Arbuscular Mycorrhizal Fungi): A case study in Indonesia. Sustainability Vol 13, 12333. https://doi.org/10.3390/su132212333.

3. **Kurniawati A.**, Gergely T., Kari Y., Zoltan T. 2023. Opportunities and challenges of bio-based fertilizers utilization for improving soil health. Org. Agr. 13:335–350 https://doi.org/10.1007/s13165-023-00432-7.

4. **Kurniawati A.**, Petra S., Yahya SH., Gergely T., Marzena S., Zoltan T. 2023. Understanding the future of bio-based fertilizers: The EU's policy and implementation. Sustainable Chemistry for Climate Action Vol 3, 100033. https://doi.org/10.1016/j.scca.2023.100033.

5. Iswahyudi, Wahyu W., Warkoyo W., Roy HS., Adi S., Zane V., Mohammed W., Shazma A., Sri Y., Adil B., Azwin S., Marcel PG., Yenni ACE., Emi Y., Sustiyana S., Sitti M., Mohammad SS., Muhammad TS., Ahmad F., Akh F., **Ari K.**, Baihaqi, Bayu AP., and Muhammad HM. 2023. Bibliometric Analysis on Contaminant Microplastics in Compost (2018 to 2022) Through VOSviewer. E3S Web Conf. 432(00015):13. The 2nd International Conference on Bioenergy and Environmentally Sustainable Agriculture Technology (ICoN BEAT 2021). https://doi.org/10.1051/e3sconf/202343200015

Abstracts published in international conferences

1. **Kurniawati A.**, Zoltan T., Gergely T. Response of growth and yield of Physalis angulata to arbuscular mychorrizal fungi and goat manure application in a high level of soil phosphorus availability under organic growing conditions. CASEE CONFERENCE 2021: CASEE universities as laboratories for new paradigms in life sciences and related disciplines. Prague: 6-8 June 2021 (Online).

6 BIBLIOGRAPHY

Bauerle, A., Müller, B., Bünemann-könig, E., Delgado, A., Herrmann, L., Stoumann Jensen, L., Kurniawati, A., Müller, T., Santner, J., Tóth, Z., & Ylivainio, K. (2021). *Protocol for Selecting Bio-Based Fertilisers to be Studied in LEX4BIO*. http://www.lex4bio.eu

Brye, J. B., Lunga, D. Della, & Brye, K. R. (2024). Rice Response to Struvite and Other Phosphorus Fertilizers in a Phosphorus-Deficient Soil Under Simulated Furrow-irrigation. *Journal of Soil Science and Plant Nutrition*, *24*(4), 7491–7506. https://doi.org/10.1007/s42729-024-02054-8

Case, S. D. C., Oelofse, M., Hou, Y., Oenema, O., & Jensen, L. S. (2017). Farmer perceptions and use of organic waste products as fertilisers – A survey study of potential benefits and barriers. *Agricultural Systems*, *151*, 84–95. https://doi.org/10.1016/j.agsy.2016.11.012

Chojnacka, K., Moustakas, K., & Witek-Krowiak, A. (2020). Bio-based fertilizers: A practical approach towards circular economy. *Bioresource Technology*, *295*, 122223. https://doi.org/10.1016/j.biortech.2019.122223

Davidson, E. A., Suddick, E. C., Rice, C. W., & Prokopy, L. S. (2015). More Food, Low Pollution (Mo Fo Lo Po): A Grand Challenge for the 21st Century. *Journal of Environmental Quality*, *44*, 305–311. https://doi.org/10.2134/jeq2015.02.0078

Directorate-General for Internal Market, I. E. and Sme. (2022, June 15). *New EU rules prepare the ground for more use of organic and waste-based fertilisers*. Https://Single-Market-Economy.Ec.Europa.Eu/News/New-Eu-Rules-Prepare-Ground-More-Use-Organic-and-Waste-Based-Fertilisers-2022-07-15_en.

El Mazlouzi, M., Morel, C., Robert, T., Chesseron, C., Salon, C., Cornu, J. Y., & Mollier, A. (2022). The Dynamics of Phosphorus Uptake and Remobilization during the Grain Development Period in Durum Wheat Plants. *Plants*, *11*(8). https://doi.org/10.3390/plants11081006

European Environment Agency. (2020). *Bio-waste in Europe turning challenges into opportunities*. https://doi.org/10.2800/630938

Frick, H., Bünemann, E. K., Hernandez-Mora, A., Eigner, H., Geyer, S., Duboc, O., Santner, J., Recena, R., Delgado, A., D´Oria, A., Arkoun, M., Tóth, Z., Jauhiainen, L., & Ylivainio, K. (2025). Bio-based fertilisers can replace conventional inorganic P fertilisers under European pedoclimatic conditions. *Field Crops Research*, *325*. https://doi.org/10.1016/j.fcr.2025.109803

Guilayn, F., Jimenez, J., Martel, J. L., Rouez, M., Crest, M., & Patureau, D. (2019). First fertilizing-value typology of digestates: A decision-making tool for regulation. *Waste Management*, *86*, 67–79. https://doi.org/10.1016/J.WASMAN.2019.01.032

Hijbeek, R., Pronk, A. A., van Ittersum, M. K., Verhagen, A., Ruysschaert, G., Bijttebier, J., Zavattaro, L., Bechini, L., Schlatter, N., & ten Berge, H. F. M. (2019). Use of organic inputs by arable farmers in six agro-ecological zones across Europe: Drivers and barriers. *Agriculture, Ecosystems & Environment*, *275*, 42–53. https://doi.org/10.1016/J.AGEE.2019.01.008

Hou, Y., Velthof, G. L., Case, S. D. C., Oelofse, M., Grignani, C., Balsari, P., Zavattaro, L., Gioelli, F., Bernal, M. P., Fangueiro, D., Trindade, H., Jensen, L. S., & Oenema, O. (2018). Stakeholder perceptions of manure treatment technologies in Denmark, Italy, the Netherlands and Spain. *Journal of Cleaner Production*, *172*, 1620–1630. https://doi.org/10.1016/j.jclepro.2016.10.162

Huygens, D., Saveyn, H., Tonini, D., Eder, P., & Delagado Sancho, L. (2019). *Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009)* (Number KJ-NA-29841-EN-N (online),KJ-NA-29841-EN-C (print)). Publications Office of the European Union. https://doi.org/10.2760/186684 (online),10.2760/551387 (print)

Jara-Samaniego, J., Pérez-Murcia, M. D., Bustamante, M. A., Paredes, C., Pérez-Espinosa, A., Gavilanes-Terán, I., López, M., Marhuenda-Egea, F. C., Brito, H., & Moral, R. (2017). Development of organic fertilizers from food market waste and urban gardening by composting in Ecuador. *PLOS ONE*, *12*(7), e0181621. https://doi.org/10.1371/journal.pone.0181621

Kacprzak, M., Kupich, I., Jasinska, A., & Fijalkowski, K. (2022). Bio-Based Waste' Substrates for Degraded Soil Improvement—Advantages and Challenges in European Context. In *Energies* (Vol. 15, Number 1). MDPI. https://doi.org/10.3390/en15010385

Kaszycki, P., Głodniok, M., & Petryszak, P. (2021). Towards a bio-based circular economy in organic waste management and wastewater treatment – The Polish perspective. *New Biotechnology*, *61*, 80–89. https://doi.org/10.1016/J.NBT.2020.11.005

Kiani, M., & Ylivainio, K. (2024). Methods for testing short- and long-term phosphorus fertilizing efficiency of products with varying solubility. *Science of the Total Environment*, *922*. https://doi.org/10.1016/j.scitotenv.2024.170965

Kominko, H., Gorazda, K., & Wzorek, Z. (2021). Formulation and evaluation of organo-mineral fertilizers based on sewage sludge optimized for maize and sunflower crops. *Waste Management*, *136*, 57–66. https://doi.org/10.1016/J.WASMAN.2021.09.040

Kominko, H., Gorazda, K., & Wzorek, Z. (2022). Effect of sewage sludge-based fertilizers on biomass growth and heavy metal accumulation in plants. *Journal of Environmental Management*, *305*, 114417. https://doi.org/10.1016/J.JENVMAN.2021.114417

Liu, S. yuan, Zada, A., Yu, X., Liu, F., & Jin, G. (2022). NiFe2O4/g-C3N4 heterostructure with an enhanced ability for photocatalytic degradation of tetracycline hydrochloride and antibacterial performance. *Chemosphere*, *307*, 135717. https://doi.org/10.1016/J.CHEMOSPHERE.2022.135717

Lupton, S. (2017). Markets for waste and waste–derived fertilizers. An empirical survey. *Journal of Rural Studies*, *55*, 83–99. https://doi.org/10.1016/J.JRURSTUD.2017.07.017

Mahmood, M., Wang, J., Mehmood, S., Ahmed, W., Ayyoub, A., Seleiman, M. F., Elrys, A. S., Elnahal, A. S. M., Mustafa, A., Wei, X., & Li, W. (2025). Influence of drought stress on phosphorus dynamics and maize growth in tropical ecosystems. *BMC Plant Biology*, *25*(1). https://doi.org/10.1186/s12870-025-06092-x

Mažeika, R., Arbačiauskas, J., Masevičienė, A., Narutytė, I., Šumskis, D., Žičkienė, L., Rainys, K., Drapanauskaite, D., Staugaitis, G., & Baltrusaitis, J. (2021). Nutrient Dynamics and Plant Response in Soil to Organic Chicken Manure-Based Fertilizers. *Waste and Biomass Valorization*, *12*(1), 371–382. https://doi.org/10.1007/s12649-020-00978-7

Min, K. J., Kim, D., Lee, J., Lee, K., & Park, K. Y. (2019). Characteristics of vegetable crop cultivation and nutrient releasing with struvite as a slow-release fertilizer. *Environmental Science and Pollution Research*, *26*(33), 34332–34344. https://doi.org/10.1007/s11356-019-05522-2

Müller, B., Herrmann, M. N., Lewandowski, I., Müller, T., Hartung, J., & Bauerle, A. (2024). The Effect of Biobased N and P Fertilizers in a Winter Wheat–

Ryegrass Crop Rotation. *Agronomy*, *14*(10). https://doi.org/10.3390/agronomy14102424

Nakagawa, A., & Sarr, P. S. (2025). Calcined low-grade phosphate rock fertilization enhances nitrogen fixation, yield, and grain quality in soybeans. *Frontiers in Plant Science*, *16*. https://doi.org/10.3389/fpls.2025.1581961

Preisner, M., Smol, M., Horttanainen, M., Deviatkin, I., Havukainen, J., Klavins, M., Ozola-Davidane, R., Kruopienė, J., Szatkowska, B., Appels, L., Houtmeyers, S., & Roosalu, K. (2022). Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector. *Journal of Environmental Management*, *304*, 114261. https://doi.org/10.1016/J.JENVMAN.2021.114261

Randive, K., Raut, T., & Jawadand, S. (2021). An overview of the global fertilizer trends and India's position in 2020. *Mineral Economics*, *34*(3), 371–384. https://doi.org/10.1007/s13563-020-00246-z

Santagata, R., Ripa, M., Genovese, A., & Ulgiati, S. (2021). Food waste recovery pathways: Challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment. *Journal of Cleaner Production*, *286*, 125490. https://doi.org/10.1016/j.jclepro.2020.125490

Silva, F. C., Cruz, N. C., Tarelho, L. A. C., & Rodrigues, S. M. (2019). Use of biomass ash-based materials as soil fertilisers: Critical review of the existing regulatory framework. *Journal of Cleaner Production*, *214*, 112–124. https://doi.org/10.1016/j.jclepro.2018.12.268

Smol, M. (2021). Transition to circular economy in the fertilizer sector—analysis of recommended directions and end-users' perception of waste-based products in Poland. *Energies*, *14*(14). https://doi.org/10.3390/en14144312

Stępień, A., Wojtkowiak, K., & Kolankowska, E. (2021). Use of meat industry waste in the form of meat-and-bone meal in fertilising maize (Zea mays l.) for grain. *Sustainability (Switzerland)*, *13*(5), 1–19. https://doi.org/10.3390/su13052857

The European Commission. (2016). *Press release Circular economy: New Regulation to boost the use of organic and waste-based fertilisers*. https://ec.europa.eu/commission/presscorner/detail/en/IP_16_827

The European Union. (2019). *EU Fertilizing Products Regulation Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU* *fertilising products and amending Regulations (EC) No 1069/2009 and (E*. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32019R1009

Tur-Cardona, J., Bonnichsen, O., Speelman, S., Verspecht, A., Carpentier, L., Debruyne, L., Marchand, F., Jacobsen, B. H., & Buysse, J. (2018). Farmers' reasons to accept bio-based fertilizers: A choice experiment in seven different European countries. *Journal of Cleaner Production*, *197*, 406–416. https://doi.org/10.1016/j.jclepro.2018.06.172

van Dijk, K. C., Lesschen, J. P., & Oenema, O. (2016). Phosphorus flows and balances of the European Union Member States. *Science of The Total Environment*, *542*, 1078–1093. https://doi.org/10.1016/j.scitotenv.2015.08.048

Vaneeckhaute, C. (2021). *Perspective Integrating resource recovery process and watershed modelling to facilitate decision-making regarding bio-fertilizer production and application*. https://doi.org/10.1038/s41545-021-00105-6

Wen, G., Huang, L., Zhang, X., & Hu, Z. (2019). Uptake of nutrients and heavy metals in struvite recovered from a mixed wastewater of human urine and municipal sewage by two vegetables in calcareous soil. *Environmental Technology & Innovation*, *15*, 100384. https://doi.org/10.1016/j.eti.2019.100384

Wester-Larsen, L., Müller-Stöver, D. S., Salo, T., & Jensen, L. S. (2022). Potential ammonia volatilization from 39 different novel biobased fertilizers on the European market – A laboratory study using 5 European soils. *Journal of Environmental Management*, *323*. https://doi.org/10.1016/j.jenvman.2022.116249

Zhao, Y., Zada, A., Yang, Y., Pan, J., Wang, Y., Yan, Z., Xu, Z., & Qi, K. (2021). Photocatalytic Removal of Antibiotics on g-C3N4 Using Amorphous CuO as Cocatalysts. *Frontiers in Chemistry*, *9*. https://doi.org/10.3389/fchem.2021.797738

Zhu, P., Shen, Y., Pan, X., Dong, B., Zhou, J., Zhang, W., & Li, X. (2021). Reducing odor emissions from feces aerobic composting: Additives. In *RSC Advances* (Vol. 11, Number 26, pp. 15977–15988). Royal Society of Chemistry. https://doi.org/10.1039/d1ra00355k