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(MATE)

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

Doctoral (PhD) dissertation

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Table of Contents

List of Figures

List of Tables

LIST OF LEGENDS AND ABBREVIATIONS

ANOVA	Analysis of variance
BBFs	Bio-based fertilizers
CMC	Component material category
CV	Coefficient of variation
df	Degree of freedom
FPR	Fertilizer product regulation
STRUBIAS	STRUvite/recovered phosphate salts, BIochars/pyrolysis materials, ASh-based products
PFC	Product function category
SS	Sewage sludge
.csv	Comma-separated values
ES	Ecosystem services
EC	Electrical conductivity
AMF	Arbuscular mycorrhizal fungi
MBM	Meat and bone meal
AD	Anaerobic digestion
LCAs	Life cycle assessments
SOM	Soil organic matter
SOC	Soil organic carbon
TSP	Triple super phospahte
GHG	Greenhouse gas
TRLs	Technology readiness levels
LCC	Life cycle cost
S-LCA	Social life cycle assessment

1. INTRODUCTION

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 is 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 on maintaining the stability of food availability.

Agriculture sector has a crucial role in achieving food security. However, its activity often contributes to high energy use. The intensive agricultural operations and unsustainable land-use management practices have caused the decline in soil health and crop yield (Jian et al., 2020). 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. For instance, Figure 1 shows that China's phosphate production places it as number one on the list of top phosphate-producing countries by a long shot (Randive et al., 2021). In this case, the EU can be largely dependent on imports of phosphorus fertilizer. On the other hand, Hungary is facing declining trends in phosphorus levels, which will soon lead to a decrease in soil productivity (Kassai & Tóth, 2020). This condition forces new consideration of renewable phosphorus management.

Chemical fertilizers are frequently imported by European agriculture (Tur-Cardona et al., 2018), yet the exclusive and excessive use of fertilizers is causing some issues. Menšík et al. (2018) reported that long-term application of conventional fertilizers (NPK) can accelerate humus mineralization and soil quality degradation with all negative consequences, such as higher availability of toxic element for plants and slow energy for soil microorganisms. Also, phosphorus use in EU was characterized by long-term accumulation in agricultural soils causing leaky losses throughout entire society (van Dijk et al., 2016). Moreover, the nutrients can run off into surface water and leach to groundwater which can pollute the environment. These issues drag the consideration for another alternative solution: bio-based fertilizers (BBFs). Shifting from chemical fertilizers to BBFs is very much expected, especially for European agriculture (Chojnacka et al., 2020).

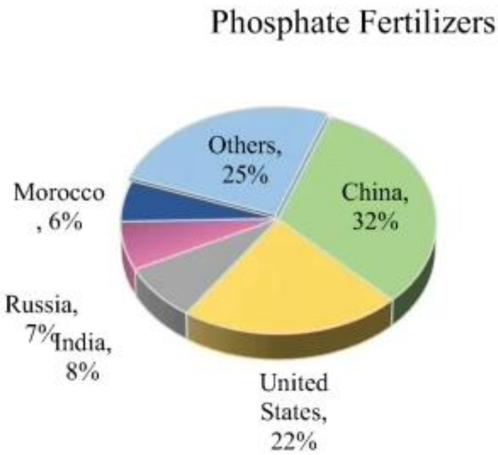


Figure 1. Top five fertilizer minerals producing countries controlling more than 50% of the global production (Randive et al., 2021).

1.2. The urgency of Bio-Based Fertilizers (BBFs) to reduce dependence upon conventional fertilizers

Bio-based products are emerging due to the global pressure to convert waste to nutrient-rich products that can be valorized 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. Moroever, the availability of raw materials for BBFs production is also abundant. In 2017, the EU-28 (28 EU Member States) generated 86 million tons 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 worse; 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).

Several studies have been done to process waste by products into bio-based fertilizers and to fulfill the preference of farmers. For example, ammonium nitrate and ammonium sulfate from animal manure have been developed through the process of (stripping-) scrubbing technology and resulted total nitrogen in mineral form similar with synthetic mineral N fertilizer produced via Haber-Bosch process (Sigurnjak et al., 2019). This potency of BBFs aligns with the farmer's preference of expecting the nutrient content in BBFs to be the same as in the conventional fertilizer. Farmers from different countries within Europe (Belgium, Denmark, France, Netherlands, Germany, Hungary, and Croatia) have common preferences for BBFs with similar nutrient content but lower price than chemical fertilizer (Tur-Cardona et al., 2018).

Moreover, in Denmark, the main barriers of using organic fertilizers are unpleasant odor and uncertainty nutrient content (Case et al., 2017). These preferences are amplified by the soil health criteria (environmental quality, agronomic sustainability, and socio-economic viability) for long-term use which must be accomplished by fertilizer industries. Furthermore, related to resource availability in BBFs production, a cross-sectorial vision is required to bridge the gap between agricultural residues science and business opportunities to promote an agricultural residue industrial ecology concept (Gontard et al., 2018). Again, BBFs role can be potentially one of the main player for the agriculture sector.

The potential use of BBFs for future fertilizer has been tested in experiments revealing decreased rate of conventional fertilizer by the addition of BBFs to substitute plant nutrients (Borges et al., 2019). Moreover, N losses (including NH_3, N_2O emissions, and N leaching) can be reduced by 50% substitution of manure for chemical N fertilizers (Guo et al., 2020). There were no significant differences in respect to product characterization and fertilizer performance of BBFs compared to conventional fertilizer (Dubis et al., 2020; Grillo et al., 2021; Sigurnjak et al., 2019). Nevertheless, the question remains about how big the impact on soil properties and plant production is. An adequate assessment approach which provides proper insight and guidance on the seasonality, regional aspects, and complexity of agricultural residue management chains is needed (Gontard et al., 2018) to check the effects of BBFs not only on crop production but also to support the circular economy.

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% 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 fertilizing 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). Meanwhile, to use the BBFs at the industrial level may lead to another issue.

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 to achieve

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. LITERATURE OVERVIEW

2.1. Fertilizer industry and sustainability

Fertilizers are fundamental in the development of crop and soil health. They are composed of main nutrients, microelements (nitrogen, phosphorus, potassium), secondary nutrients (calcium, sulfur, magnesium), and microelements (zinc, molybdenum, boron, manganese, and iron). The use of fertilizers allows plants to produce high yield contributing to develop a food chain that allows the majority of the world's population to be fed.

Misuse of agricultural fertilizers have undoubtedly occurred, and its impact on the environment needs to be minimized. Comparing the risk of fertilizer application with the benefits for food production is important to be considered because proper crop nutrition plays a vital role in maintaining the world's food supply. The fertilizer industry is made up of companies who represent the entire supply chain from production to distribution to retail, all working together to deliver fertilizer to farmers in a safe, timely, and sustainable manner (The fertilizer institute, 2016).

The employment of fertilizers not only increases crop productivity, but also alters soil physico-chemical and biological properties. However, continuous utilization and the overuse of chemical fertilizers show the opposite effects such as a decrease in soil organic matter (SOM) content, hardening the soil, reducing soil fertility, pollution of air, water, and soil, and lessened important nutrients of soil and minerals, thereby bringing hazards to environment (Pahalvi et al., 2021). Moreover, manufacture and application of synthetic N fertilizers in Chinese croplands is contributing as source of agricultural GHG emissions (Chai et al., 2019).

The production of fertilizer is energy intensive. Natural gas is used in the production of nitrogen and in manufacturing dry phosphate fertilizers. Natural gas can account for between 70 and 90 percent of the nitrogen fertilizer manufacturing cost (The fertilizer institute, 2016). Therefore, fertilizer industry faces challenges not only in terms of their side effects to the environment, but also in terms of their production. The other issues that may arise are finite raw materials, prices, and global crisis.

The price of natural gas increase significantly by approximately 200% in 2021 followed by the dynamic increase of price of CO_2 emission allowances causing the price of nitrogen fertilizer increased by 300% (Chojnacka et al., 2022). This situation results the high cost of food production and in turn, will translate into a problem with food safety and food security.

2.2. Understanding the needs of bio-based fertilizers

BBF has been developed as (i) alternatives of traditional fertilizers, (ii) utilization of renewable agricultural side products, and (iii) a green deal implementation throughout the world which is supported by European Commission as a legal instruction to implement circular economy in terms of sustainable agriculture. European Commission set a goal of 30% reduction of nonrenewable resources in fertilizer production (Chojnacka et al., 2020). National policies, including EU Fertilising Products Regulation (FPR) will radically change the way fertilizers receiving the labelling requirements provided on the products (Regulation 2019/1009 of The European Parliament and of The Council). This regulation stimulates fertilizer industries to produce sustainable BBF for food and its production.

In this case, during fertilizer production, fertilizer industries may apply the concept of circular economy based on reuse, valorization, recycling, and exploitation of natural cycles in elaboration of bio-based fertilizer technologies (Chojnacka et al., 2020), instead of using extremely energy-intensive and requiring a large amount of natural gas. The waste by-products may fulfill the limit values of heavy metal and hygiene indicators for safety fertilizers by the technology process which is permitted by the regulations. In this context, the use of nutrients and valuable substances is derived from safe and qualitatively suitable by-products and waste, in order to close the cycles and reduce raw material imports as well as the extraction of nonrenewable raw materials (Stürmer et al., 2020). These by-products also can be seen in Table 1. Bio-based fertilizers hold the advantage of recycling nutrient-rich side stream and using less energy and nonrenewable resource consumption during manufacture compared to conventional fertilizers (Jensen et al., 2020).

The application of bio-based material on soil shows various effects to the soil due to the changes of organic material and microorganism activities depending on the bio-based material used and the soil site. Some findings related to the use of BBFs on crop production also were shown in Table 1 covering different component material categories (CMC) as raw materials. Consideration to define PFC was difficult since the products must cover a broad range of organic (solid and liquid organic fertilizer were ≥ 15% and ≥5% carbon (C) organic, respectively), organo-mineral (solid and liquid organo-mineral fertilizer were ≥ 7.5% and ≥3% C organic, respectively), and mineral type fertilizers (straight and compound solid inorganic macronutrient fertilizer) to be mentioned as fertilizer.

Table 1. Summary of BBFs studies based on the rules of the new EU Fertilising Products Regulation (2019/1009)

Raw material	Technology	CMC	Contribution	Main finding
Food wastes	Hydrolysis	6 (food industry by-products)	Ma et al., 2017	The solid residue produced had good quality in terms of the NPK and heavy metals contents, which can be directly converted to biofertilizer.
Meat and bone meal (MBM)	Called tankage was obtained from Baker Commodities Inc. (Kapolei Industrial Park, HI)	10 (animal by-products)	Silvasy et al., 2021	MBM was an effective source of N for sweet corn production in the tropics and a split application of MBM may reduce potential groundwater pollution.
Poultry litter biochar	Not mention	14 (biochar/pyrolysis product)	Solaiman et al., 2020	The use of biochar could be an effective approach in relation to plant growth, yield, nutrient uptake, and improved soil fertility of sandy soils.
Struvite	Crystallisation	12 (recovered P-Salts)	Min et al., 2019	The struvites recovered from livestock wastewater are considered to have a high value as fertilizer due to contain more than 20% potassium oxide and lower of heavy metals concentration, such as copper and zinc.
Biowastes (olive mill wastewater sludge, poultry manure, and green waste)	Composting	3 (compost)	Mekki et al., 2019	A significant increase in soil organic matter and soil organic carbon with relation to biowaste compost quantities applied on Mediterranean soils under arid climate which is poor in organic matter content.
Energy crops (e.g., silage maize and silage winter wheat) and animal wastes (e.g., poultry manure, cattle and swine slurry)	Digestion	5 (digestate other than fresh crop digestate)	Grillo et al., 2021	Both digestate fractions gave agronomic performances comparable to those of conventional fertilizers suggesting that they can be an effective substitute for conventional fertilizers in intensive cropping systems, but long-term experiment is needed to evaluate solid digestate fraction sustainability.

Source: author compilation, 2024

The EU FPR manages the bio-based products based on product function category (PFC) which can be classified not only as fertilizers (PFC 1) but also as liming material (PFC 2), soil improver (PFC 3), growing medium (PFC 4), inhibitor (PFC 5), plant bio-stimulant (PFC 6), and fertilizing product blend (PFC 7). The regulation sets different minimum nutrient contents for the PFC. For instance, organic waste processed by anaerobic digestion can be concluded as fertilizer or soil conditioner depending on the carbon organic and the minimum macronutrient content and limit values for heavy metals generally which do not pose problems for fertilizer classification (Stürmer et al., 2020). Moreover, according to the experiment of Masud et al., (2020) in the pot experiment, poultry litter biochar was the best choice for the amelioration of acid soils due to the increased rate in soil pH, even it helped to increase soil available P, plant growth, and nutrient uptake.

BBFs derived from sewage sludge are allowed by the Fertilizer Regulation in certain products. Criteria for "STRUBIAS" materials (STRUvite/recovered phosphate salts, BIochars/pyrolysis materials, ASh-based products) was published in 2019 and is the basis for new CMC. Except for biochar, which is not permitted from sewage sludge, struvite and ash-based products will be authorized as ingredients for EU fertilizers (EurEau, 2021). Sewage sludge represents a very relevant side stream that should be taken into account despite restrictions and potential risks. The TRIZ approach (Teoria reszenija izobretatielskich zadacz — Rus., Theory of Inventive Problem-Solving — Eng.) identified sewage sludge (SS) as waste with a large potential for P recovery (up to 90%) (Jama-Rodzeńska et al., 2021).

Sewage sludge is prohibited by EU FPR (2019/1009) due to the risk of toxicity, but it can be managed by treatments. Biotechnology for intensive aerobic bioconversion of sewage sludge and food waste produced a powder, stable, and nontoxic fertilizer for the germination of plant seeds, and addition of 1.0 to 1.5% of this fertilizer to the subsoil increased the growth of different plants tested by 113 to 164% (Wang et al., 2004). Besides, (Frišták et al., 2018) reported the possibility of sewage sludge conversion by pyrolysis process to stable and valuable products with a 2- to 3-fold increase of phosphorus content.

2.2.1. Effects of bio-based fertilizers on sustainability of plant production

The effects of BBFs on crop production can be observed by the increase of plant quality and quantity due to the availability of nutrients in the soil. Its availability is also supported by healthy soil. There is a relationship between soil health indicators and crop productivity due to interactions among sustainable agricultural practices (Lehmann et al., 2020). Research revealed that recovery and recycling of nutrients from chicken manure possess similar plant response properties such as those of conventional fertilizers towards crop yield and quality while improving soil agrochemical properties (Mažeika et al., 2021). On the other hand, the digestate from poultry manure presented high values of pH and EC which are important on nutrient uptake process, although both parameters were kept within the appropriate soil range for crop growth proven by increase of fresh weight of lettuce (Mortola et al., 2019).

Manure nutrient with additional plant residues even can remain in the soil until the next season due to slow-release effect. However, the combination of management practice is also important. For example, the application of manure was not necessary for mustard greens cultivation if soybean or corn residues were added in the second season, and there were residues from manure application in the first season (Kurniawati et al., 2017). In another case, sandy soil amended by biochar and compost had effects on soil physical and chemical characteristic for more than 1 year after application (Elshony et al., 2019).

On the other hand, the recovered struvite is also an effective fertilizer as its nutrient-releasing rate is very slow. It decreased P losses when applied at a proper rate, but the inhibition of plant growth happened when overdosed (Arcas-Pilz et al., 2021; Min et al., 2019). Furthermore, struvite application decreased the lettuce biomass because of the high soil pH in calcareous soils, and external P fertilization together hampered Zn uptake by the lettuce, even though this effect did not happen to cabbage biomass (Wen et al., 2019). Therefore, the plant types need to be considered in struvite usage as P fertilizer in the high soil pH causing unbalance micronutrient uptake to the shoots and roots.

Regardless of struvite, the use of digestate fractions (solid and liquid) as fertilizers also depend mainly on soil characteristics rather than the quantity (carbon loading) and quality (decomposability) of the organic material applied (Panuccio et al., 2021). Thus, the characteristic of BBFs is also specified by considering the soil types in local field condition to match the crops since the consistency and release of nutrients in BBFs vary depending on raw materials and technology production. In matching crops, BBFs is still not powerful enough compared to conventional fertilizer which needs a longer time to do the research to see the compatibility for each crop.

Furthermore, the short- and long-term effects of bio-based material application vary and need to be studied. Soil health tests by Roper et al., (2017) showed nonsignificant difference in regionally unique soil conditions (mountain, piedmont-moldboard plowing, and coastal plain) for long-term agronomic management (chemical and organic fertilizers combined with or without tillage) trials, even no correlation to the crop yields. On contrary, different fertilization treatments changed soil microbial community, while cattle manure and its combination with NPK fertilizer significantly increased the content of soil organic carbon, total nitrogen, soil microbial biomass carbon, and soil microbial biomass nitrogen under long-term fertilization (Z. Guo et al., 2019). Based on the research, long-term experiments showed the potential of BBF utilization sole or mixed with conventional fertilizer.

2.2.2. Effects of bio-based fertilizers on soil ecosystem services

The challenges of using BBFs are mostly about contaminants or toxicity in the soil ecosystem. The harmful organic substances could be possible to enter the food chain and increase antibiotic resistance in the agricultural soil. However, along with the development of research, the side effects could be reduced. In Table 2, we can see that problems of BBFs were used as research gap of the researchers to improve the quality of BBFs in order to be accepted in society as promising sustainable fertilizer.

Table 2. Challenges and opportunities of using BBFs in ecosystem services

Challenges – Solutions	Opportunities
• Antibiotic and microplastic residues - No direct application of BBFs • Toxicity of heavy metals - Proper waste management • Pathogen exposure - Sanitation process • Salts accumulation - Fertilizer management practices	• Improve crop quality • Increase the uptake of micronutrients • Promote soil biodiversity • Help remediation process

Source: author compilation, 2024

It cannot be disclaimed that the use of BBFs in agriculture system does not pose a threat to the environment, including water pollution and human health. (Zhou et al., 2020) reported that in China, manurebased fertilizer derived from intensive animal farming has risks to antibiotic exposure which remains as residues or pollutants in organic fertilizers and posed a high, short-term risk to plants but not to soil invertebrates. Moreover, digested food waste as fertilizer in Sweden had relatively large cadmium fow, so improvements in the digestion system is needed to avoid the negative impacts (Chiew et al., 2015).

To keep the purity of BBFs when applied to the soil, Bousek et al. (2018) stated that antibiotic contamination could be reduced through mesophilic and thermophilic anaerobic digestion (AD). This result was in line with the review from Santagata et al. (2021) that mentioned AD is an efective kind of treatment to convert waste into energy used as biofertilizer and to avoid harmful impacts on human health and the environment. The characteristics of manure and other waste streams could be enhanced through processing; it could be transformed into an alternative bio-based fertilizer recycling the nutrients within the farming sector (Tur-Cardona et al., 2018).

Risks coming from BBFs applications are caused by improper process of waste treatments. For example, an incineration process is capable of recovering a certain amount of fly ash and bottom ash as by-products, but both of them are potentially dangerous materials, containing heavy metals and toxic substances (Santagata et al., 2021). On the other hand, direct land application of chicken litter could be harming animal, human, and environmental health due to contamination of *Eschericia coli, Coliform bacteria, Actinobacillus and Salmonella* (Kyakuwaire et al., 2019). So, the assessment of BBF production requires multilevel and multiscale solutions to set standards for safe disposal of organic wastes. Composting of starting materials for BBFs, such as biowaste, could offer an alternative for lowering the risk of environmental contamination (Urra et al., 2019). Heavy metal concentration is one of obstacles for utilization of nutrient-rich side streams and their removal needs to be considered when choosing technologies for preparing BBFs to ensure food and feed safety in the future.

After following the procedures of BBFs production focusing on its biosecurity, the contamination on BBFs can be assessed by life cycle assessment (LCA). In general, this method is used to evaluate potential burdens and depletion of resources throughout a product's life cycle (Santagata et al., 2021). Based on LCA, phosphorus recovery through struvite precipitation in wastewater treatment had a net environmental cost (Sena et al., 2021), while the use of chemical fertilizer yielded a signifcantly high impact on freshwater eutrophication in the conventional lettuce cultivation system (Foteinis & Chatzisymeon, 2016). This LCA is important to consider the benefit of nutrient recovery and the effects on the environment.

Even though the use of BBFs considered is safer than conventional fertilizers in terms of environmental effects in the long term, the 4R (right product, right time, right place, and right rate) practices should also be implemented to reduce the consequences in the soil. Extensive fertilization using manure or conventional fertilizer find their way to loss through leaching or run off causing severe pollution and eutrophication, especially during rainfall events (Cui et al., 2020). Kurniawati et al. (2021) and Lourenzi et al. (2021) revealed that the excessive nutrients from livestock wastes can be used as nutrient sources for plants to close nutrient cycles, but excess use of organic fertilizers just increases soil P stock, vulnerable for losses. Hence, soil management practices combined with the use of novel livestock-based fertilizer products are needed to know the limit of BBF utilization.

Human health is the main priority of food production which depends on the food quality from farm feld. Thus, BBFs production prioritizing hygienization could be expected as safe fertilizer. Conventional fertilizer substitution by using BBFs affects not only nutrient content in the soil but also crop quality in the human diet. Mažeika et al. (2021) reported that the application of organic and organomineral fertilizer increased the amount of crude protein in wheat grains, similar to that obtained after the application of conventional fertilizer. Besides, compared to single superphosphate, P fertilization from struvite promoted Mg and K accumulation which are considerable quantity of nutrients for human health (Wen et al., 2019).

Another research also showed the effects of new environmentally friendly fertilizer obtained by valorization of post-extraction biomass residues of alfalfa (*Medicago*) and goldenrod (*Solidago*) to increase the uptake of microelements (Zn, Cu, and Mn) by natural chelating (Izydorczyk et al., 2020) which counter malnutrition due to Zn deficiency, especially in sub-Saharan Africa and South Asia (Wessells & Brown, 2012). According to Ibrahim et al. (2022), biochar based MgO increased soil bacterial diversity due to the increased soil pH and surface properties, so it provided habitat for the colonization, hence, a potential increase in nutrient cycling.

The capability of BBFs to improve soil biological properties is the advantage that conventional fertilizer cannot have the function in the long-term application. However, the combination of both fertilizers can maximize the function due to proper nutrient content from conventional fertilizer complementing BBFs in increasing microbial activity in the soil. Xu et al. (2020) reported that animal manure and a mixture of chemical fertilizer and straw increased the relative abundance of *Actinobacteria, Proteobacteria,* and *Ascomycota* as well as the activity of β-glucosidase and invertase. Enzyme activity has a role in the degradation of soil organic matter and plant residues.

The development of nutrient side streams refers to product function category, but it also can be a double benefit depending on the dominancy of the product function. For instance, the use of MBM had the effect of providing nutrients and as bio stimulation agent for enhancing remediation of oil-contaminated soils compared to natural attenuation (Liu et al., 2019).

2.3. Biomass valorization methods

Composting is one of the most popular methods of biomass valorization and known as a biological decomposition process of organic matter that provides the development of thermophilic temperatures as a result of biologically generated heat. According to Doña-Grimaldi et al. (2019), composting has some advantages, such as tool for managing and recycling waste in large quantity and contributing to reduce persistent organic compounds. On the other hand, the obvious disadvantage of this process is the loss of nitrogen in the form of volatile NH_3 (Chojnacka et al., 2020).

Anaerobic digestion (AD) is part of biorefinary process used to produce energy from organic waste. It has a three-stage process made up of hydrolysis, acetogenesis, and methanogenesis. In the last stage, the digestate co-produced is chemically characterized and assessed as fertilizer (Monlau et al., 2021). An overview of different reactions occurring in the AD process and the bacterial groups involved is shown in Figure 2. Chojnacka et al. (2020) mentioned that the application of one type of biomass for the AD process limits the production capacity and the use of AD is not possible where a large amount of organic waste (including food waste and green waste) is produced, e.g. in large agglomerations. The advantages given by the use of digestate as fertilizers depend mainly on soil characteristics rather than quantity (carbon loading) and quality (decomposability) of the organic material applied (Panuccio et al., 2021).

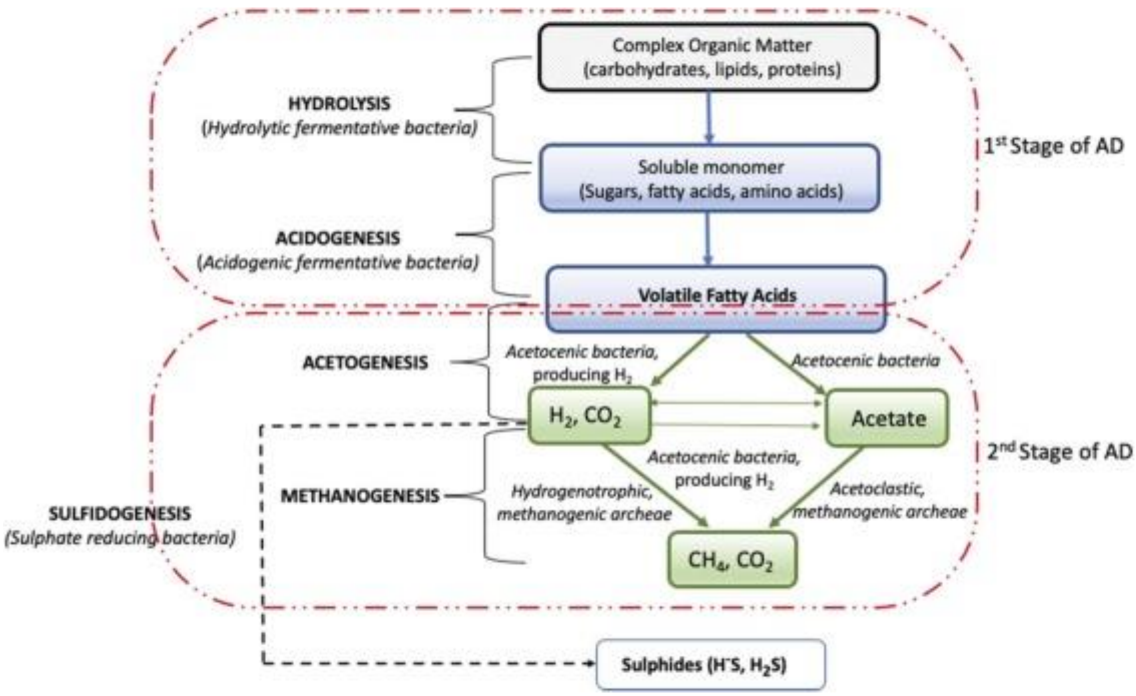


Figure 2. An overview of different anaerobic digestion reactions together with the bacteria groups involved (Okolie et al., 2022).

The most popular procedure for waste thermal biomass processing is incineration. Basically, there are some thermochemical processes (e.g., combustion, gasification, and pyrolysis) applied to convert biomass into energy vectors, generate a huge amount of residual ash. These ashes are mainly in landfills, occupying a large area of applicable land and contaminating the environment. Therefore, a suitable solution must be chosen to address the problems associated with the disposal of biomass ash. One of the by-products of biomass incineration is ash. Ash from biomass is a potential fertilizer for crops and forests. According to Chojnacka et al. (2020), if a separate collection of ash from households fired with charcoal could be applied, it would be possible to obtain a homogeneous waste that could be used for agricultural purposes. Furthermore, a study by Luyckx et al., (2021) showed that the P recovery potential of poultry manure ash, sewage sludge ash and meat and bone meal ash had a distinct P mineralogy. Moreover, the composition and advantages of the ash depend on the type of biomass and their origin (Chojnacka et al., 2022). The drawback is that they often have a high content of heavy metals that is dangerous to the environment and crops.

Thermochemical conversion processes such as gasification or pyrolysis represent relevant steps in the treatment of different kinds of biological materials and disposal of hazardous wastes (Frišták et al., 2018) and pyrolysis materials may be used as a nutrient source for plants. The addition of pyrolysis materials to soils may lead to unique interactions that influence the soil's physical properties such as porosity, particle size distribution, density and packing (Huygens et al., 2019). The result of pyrolysis is three fractions which are syngas, bio-oil, and biochar. Biochar as a carbon rich product obtained from thermal decomposition of organic material with the main application as soil amendment or fertilizer. The application of biochars to soil can increase soil C sequestration, reduce atmospheric CO_2 concentrations, improve physico-chemical soil quality and alter the content and availability of nutrients (Frišták et al., 2018). In some cases, the thermochemical processes can be combined with biological processes resulting in reducing the environmental impact compared to a standalone process. Hybrid pyrolysis-anaerobic digestion processes are promising from economics and ecological perspectives (Okolie et al., 2022).

2.4. Phosphorus nutrient recovery and sustainability

Phosphorus is essential for life and often limits the ecosystem productivity, including agroecosystems. However, the production is dependent on finite phosphate rock resources used as chemical fertilizer. Moreover, the availability of phosphorus in the soil absorbed by plants is a challenge due to solid nature of P-based compounds. Unlike other nutrient cycles, the P movement is slower from living organisms into soil, water, and sediment (Sarvajayakesavalu et al., 2018).

On the other hand, recycling P within human food and waste management systems is very limited. Instead, massive P losses to water bodies and landfill pollute the environment causing accumulation and eutrophication, defined as the excessive production of organic water in the ecosystems. Tonini et al. (2019) showed that phosphorus fertilizers sourced from secondary raw materials (sewage sludge, manure and meat and bone meal) are less environmentally impact than mining P containing rock up to 81%, 50% and 10%, respectively.

To mitigate the environmental pollution due to accumulation of phosphorus in the soil and ecosystems, while looking at alternative for P conventional fertilizers, P recovery and recycling can be a solution. This also will help to close the loop of P cycle by harvesting nutrients in waste stream. According to Roy (2017), to start the P recycling process, the first step is to identify sources of P available for recovery. The next step is to explore opportunities for synergy that would disqualify it: over-reliance on nonrenewable energy, inadequate P recovery, public health risks, and poor fertilizer value. The last step is to check the viability and scalability as a function of sustainability and economics.

Possible techniques for P recovery include a wide spectrum of technologies, such as P precipitation as struvite, sludge incineration with P recovery from ash, and the other techniques. Sarvajayakesavalu et al. (2018) mentioned that recovery can occur at all stages of the P cycle (Figure 3). There are also different strategies that can be used to recover phosphorus from different sources.

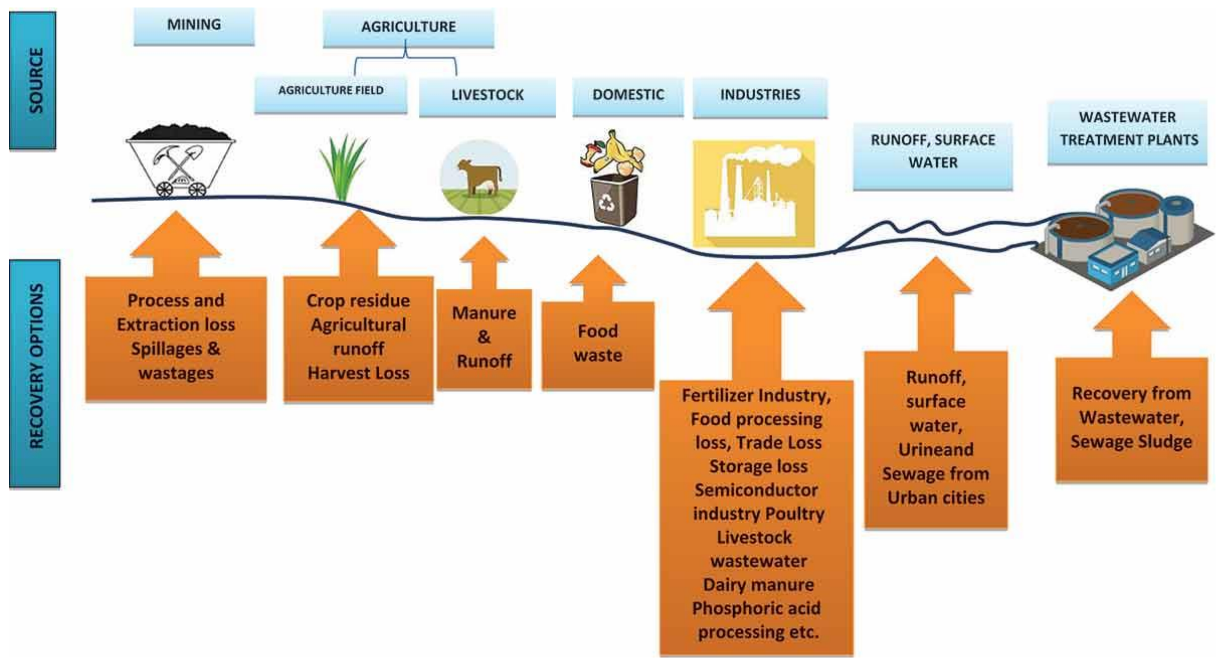


Figure 3. Phosphorus recovery options (Sarvajayakesavalu et al., 2018)

While thinking about sustainability during P nutrient recovery, other critical elements, such as carbon and nitrogen also need to be involved. Recovering and recycling P requires energy and carbon inputs are needed to facilitate some processing strategies (e.g. to manage the C:N ratio during composting) (Roy, 2017). Nutrient recovery is a complex process for a long-run implementation. The goals and the effects of the process will be the equal cases that need to be considered.

2.5. Legal areas affecting fertilizers use in the European Union

The EU intends to set an example for the rest of the world by leading climate action and promoting sustainable agriculture in a low-carbon economy through the European Green Deal (EGD) to minimize the use of fertilizers (The European Council, 2019). The EGD offers a singular opportunity to minimize the use of synthetic chemicals and fertilizers. For instance, the Farm to Fork Strategy seeks to look up the fairness, health, and food system sustainability (The European Commission, 2020a).

Several restrictions that limit the use of chemical pesticides and require the use of biologic and sustainable goods support the EGD. Furthermore, soil nutrients, which are mostly dependent on external input, have been addressed in the Zero Pollution Action Plan (The European Commission, 2021). The strategy calls attention to soil contamination brought on by heavy pesticide usage in agriculture (Jacquet et al., 2022) and suggests a 50% cut in the use of chemical pesticides by 2030, along with a 50% cut in the use of more dangerous pesticides. Additionally, the fertilization governance of the Birds Directive (The European Parliement and The Council, 2010) and the Habitats Directive (The European Council, 1992) under the minimal requirement of Common Agricultural Policy (CAP) also manage preserving biodiversity and listing endangered species (Garske et al., 2020).

On the farmer's side, they must follow a set of Cross-Compliance (CC) to receive government subsidies (The European Council, 2017). The CC guidelines for fertilizer regulation, which concentrate on minimizing land management and considering condition of local site, aim to prevent soil erosion, maintain soil organic matter, and potentially lower phosphorus (P) losses.

The legal basis of P management at the EU level is the Waste Framework Directive, which was amended in the summer of 2018 by Directive 2018/85 (Garske et al., 2020). For example, Directive 86/278/EC known as the Sewage Sludge Directive (SSD) about the use of sewage sludge was the first of the specific directives on the use of waste in agroecosystems (The European Council, 1986). Then, sewage sludge is also used for fertilization and set limit for the concentration of heavy metals. However, the SSD is not ambitious enough, and some European countries have set more stringent national standards (Duquennoi & Martinez, 2022). In line with the prevention principle, the SSD's primary goal was to avoid any negative consequences sewage sludge use in agriculture would have on the soil, plants, animals, and public health. The SSD is now considered outdated and is under review considering new scientific knowledge on the risks of organic pollutants and pathogens and the available sludge treatment technologies (The European Council, 1986). According to the new EU Fertilising Productions Regulation (FPR) (The European Union, 2019), sewage sludge is not included in the scope as a direct input material due to concerns about contaminants like heavy metals, pathogens, and emerging pollutants. However, the FPR does not prevent the use of materials derived from treated sewage sludge, provided they can meet the safety and quality requirements through a specific "end-of-waste" process or a dedicated national regulation.

Another policy that affects fertilizer industries is Climate Change Policy. There is a draft of regulation of the European Parliament and of the Council establishing the framework to achieve climate neutrality and to amend Regulation (EU) 2018/1999 (The European Council, 2021b) and to develop a climate-resilient region. The long-term goal of the new EU Strategy on Adaptation to Climate Change (The European Council, 2021a) is for the EU to transform a climate-resilient civilization by the year 2050 that has fully adapted to the unavoidable effects of climate change. Nitrogen fertilizer manufacturers are among the sectors most at risk of carbon leakage due to the industry's emissions intensity and exposure to international trade (Inguscio, 2022).

The P and nitrogen (N) management are also mentioned in Water Policy. In this context, the EU Nitrates Directive, which limits the permissible nitrate content of water bodies to 50 mg/l, is vital and aims to prevent eutrophication. Meanwhile, the Urban Waste Water Treatment Directive (UWWTD) is imperative for sustainable P management and mandates that P be removed from wastewater. A method for phosphorus recovery may be used and will be revised in the new UWWTD, but they are currently under discussion. So, soil and water legislation should effectively limit agricultural P inputs to water bodies, if not, then to what extent fertilization legislation can comply these (Garske et al., 2020).

The EU Biodiversity Strategy is a part of the EGD and aims to stop the EU's ecological services and biodiversity from disappearing. The Biodiversity Strategy is expected to work with the farm-to-fork strategy and the revised Common Agricultural Policy (CAP), with the primary target of having at least 25% of EU agricultural land under organic farming by 2030. Agroecology should be promoted as it can incorporate natural processes and ecological principles into farming techniques (The European Union, 2021b). Moreover, this program is connected to the EU Soil Strategy 2030 for healthy soil by 2050, which sets out a framework and actions to preserve soils and assure their sustainable use (Chevillard et al., 2022). It also notifies a new Soil Health Act

(The European Union, 2022) by 2023 to ensure a level playing field and a high level of environmental and health protection. As regards the use of fertilizers, the framework states that they should be applied according to the needs of the crops grown, avoiding over-application, and aiming to reduce the amount of nitrogen and phosphorus leaching from soil by 50% by 2030 (The European Union, 2021a), in line with the objectives of the Farm to Fork strategy. Summary of the policies related to the fertilizer issues can be seen on Table 3 below.

Table 3. Fertilizer Policy in the EU

Policy Area	Legislation	Type	Effect on Fertilizer Use
European Green Deal (COM/2019/ 640 final)	Farm to Fork - COM/2020/381 final (The European Commission, 2020a)	Strategy	20% less fertilizer uses and at least a 50% reduction in nitrogen losses without deteriorating soil fertility.
	Zero Pollution Action Plan - COM/2021/400 final (The European Commission, 2021)	Strategy	By 2030, usage of chemical pesticides will be reduced by 50%, while use of more dangerous pesticides will be reduced by 50%.
Circular Economy	Zero waste programme for Europe - COM/2014/398 final (The European Commission, 2014)	Strategy	The key area of the CE implementation is to increase sustainable waste management.
	First CE Action Plan - COM/2015/614 final (The European Commission, 2015)	Strategy	Set of legislative proposals on waste management and reduction of waste landfilling.
	Second CE Action Plan - COM/2020/98 final (The European Commission, 2020b)	Strategy	Development of the Integrated Nutrient Management Action Plan (INMAP), reviewing directives on wastewater and sewage sludge management,
Common Agricultural	Cross-compliance (C/2022/3390)	Regulation	To maintain soil organic matter levels, reflect site-specific

Policy Area	Legislation	Type	Effect on Fertilizer Use
Policy (CAP)			circumstances, and perhaps limit P losses, minimal land management is required.
	Habitats Directive (92/43/EEC)	Directive	To protect biodiversity, e.g., nutrient-poor grasslands which are sensitive to fertilization.
	Birds Directive (2009/147/EC)	Directive	Agricultural management to meet the goals of habitat and species protection.
Waste Policy	Sewage Sludge Directive (86/278/EEC)	Directive	Preventing sewage sludge has potentially negative effects on soil, plants, animals, and human health.
Climate Change Policy	European Climate Law (PE/27/2021/REV/1)	Regulation	By 2030, GHG emission levels must be reduced by at least 55% from 1990 levels.
Water Policy	The Nitrates Directive (91/676/EEC)	Directive	Demands that Member States develop action plans to lessen nitrogen eutrophication brought on by agricultural sources and to stop additional water contamination.
Biodiversity Policy	EU Soil Strategy for 2030 (COM/2021/699 final)	Strategy	The reduction of nutrient losses from fertilizers to the environment by 50% and the use of nitrogen fertilizer is decreased by 20%.
Soil Policy	Soil Health Legislation (2022/C 290/21) (Currently under adoption by the European Commission)	Possibly a Framework Directive, based on TFEU 191 and 192	Foreseen requirements towards member states to adopt soil protection measures and restore soils to their healthy state.

Source: author compilation, 2024

2.5.1. Current regulation related to bio-based fertilizers in the European Union

Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) is the EU's instrument for managing the risks presented by chemical substances for human health and the environment that is used to regulate the use of conventional fertilizers under the scope of the European Union Regulation 1907/2006 (The European Union, 2006). Furthermore, the current legislation regarding bio-based fertilizers the EU has adopted the 2019/1009 directive of the European Parliament and of the Council for marketing fertility enhancers on the EU market which entered into force in the summer of 2022 (The European Union, 2019).

According to Garske et al. (2020), as part of the CE Package, current legislation aims to reduce the dependence upon mineral/fossil fertilizers, benefit the environment and the EU's economy and promote a higher use of fertilizers from organic sources. The regulation adopted by the Council harmonizes the regulations for fertilizers produced from phosphate minerals and organic materials or secondary raw materials in the Union (Kratz & Hermann, 2020). It thus creates new opportunities for their large-scale production and market sale. The regulation establishes harmonized limits for some of the pollutants found in conventional fertilizers, such as cadmium. The essence of the new regulation is that any product that meets the requirements of the regulation can be placed on the market in all EU Member States if the conformity of the product is certified by an accredited conformity assessment organization. Moreover, establishing regulatory levels for hazardous contaminants in these products will reduce their adverse effects on the environment and open the single market to fertilizers made from organic waste. Additionally, it might lower Europe's reliance on foreign fertilizers (The Your Europe, 2022).

According to the regulation, CE-marked EU plant fertilizers must meet specific requirements to enter the EU's internal market comfortably. The new regulation will have two categories, one of which is Product Function Category (PFC), which includes fertilizers, liming substances, soil improvers, growing media, inhibitors, plant bio stimulants, and mixtures. The other category is the Component Material Category (CMC), which includes the following: original raw materials and their mixtures; plants, plant parts, extracts; compost; fermented fresh vegetable products; other fermented products; food industry byproducts; microorganisms; nutrient polymers; other polymers; substances produced from animal by-products (Ramawat & Bhardwaj, 2022). The product that complies with the regulations for these categories is considered safe to use (The European Union, 2019).

These requirements include, among other things, the maximum permissible level of pollutants, the use of specific categories of ingredients and labelling. The three-year transition period will provide organizations time to modify their manufacturing procedures and adhere to legal requirements. It establishes the safety and quality requirements for fertilising products sold across all EU countries. It replaces 27 differing sets of rules with one single, coherent set for the whole EU.

Organic-based fertilizers are one of the new fertilizing products targeted by the new regulations because of their circular and resource efficient nature. The EU has created new rules related to fertilizing products to contribute to the European Green Deal and, in the face of the energy crisis, to facilitate the production of bio-based fertilizers. It keeps harmonization optional by allowing non-harmonized fertilizer products to be sold on the internal market in compliance with national legislation and the principles of free movement. Manufacturers of fertilizers without CE marking still can market their products on the national markets (The European Union, 2016). The license applicant can therefore choose a more favorable procedure. Through mutual recognition, EU Member States usually accept non-hazardous industrial products authorized in the other country (Dahlbergh et al., 2020). This condition limits the development of standard protective requirements. At the same time, based on the principle of equivalence of protection derivable from the European treaty (The European Union, 2012), every member state has the right to maintain the protection it previously maintained in its territory. In general, the rules and activities that occur in BBFs support can be seen in Figure 4.

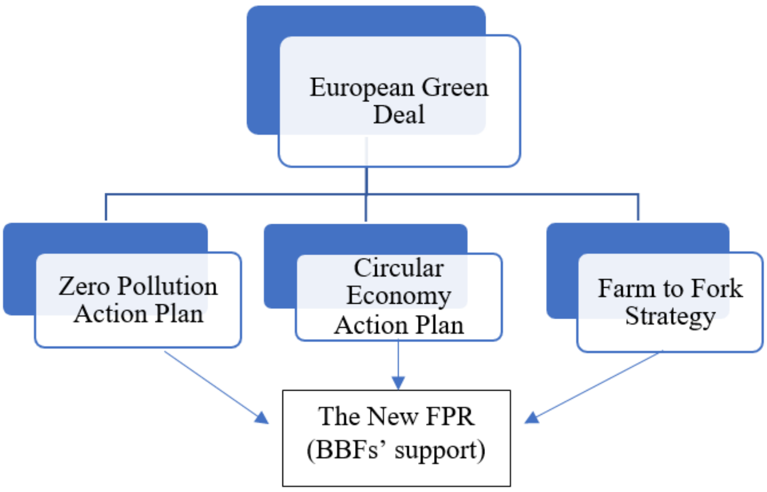


Figure 4. From The European Green Deal to The New FPR

2.5.2. The challenges of the new fertilizer product regulation (FPR)

Policy implementation and significant regulatory efforts have been made in the EU towards waste recycling and recovery as alternative raw materials to reduce the dependency on conventional fertilizers in a circular economy. The EU FPR shifted the paradigm of the 2003/2003 regulation, which only covered conventional fertilizers. Due to covering organic and secondary resources, the new regulation mandates to follow what the product is made of and under which category it would be put on the market. Thus, it regulates not only the products' characteristics but also the input materials contained in every fertilizing product. Therefore, the goal is to produce safe and high-quality fertilizers, including those derived from waste that can be labelled to be freely traded between Member States.

However, there are some challenges to implementing the new EU FPR. In the new draft of FPRs, contaminants are only sometimes expressed in the most appropriate forms. For instance, macroalgae – an essential component of some bio-based fertilizers and other fertilizing products – contain high levels of organic arsenic, such as arse-no-sugars which is almost entirely harmless to humans and animals, and almost no inorganic arsenic (Lähteenmäki-Uutela et al., 2021). However, in the proposed regulation, arsenic is only expressed as 'total arsenic' without differentiating its two forms. In this case, the regulation is not strict enough to distinguish and define the toxicity or maximum residue limit for food and feed.

Despite the new regulation, which is limited to covering all raw materials and defining the maximum residue values for fertilizers, fertilizer companies still need help producing BBFs based on policy standards. However, FPR compliance is not obligatory since fertilizers can be marketed as either "national fertilizers" (subject to national regulation) or "EC fertilizers", permitting distribution in the EU (FPR compliant) and receiving the CE mark. The new FPR (EU) 2019/1009 promotes higher use of fertilizers from organic sources, ensuring soil health and food safety. However, there is a limit to the regulation on how to guarantee the highest agricultural land productivity while safeguarding human beings from contaminants (Marini et al., 2020). The CMC and PFC are limited to covering all raw materials, so it would be a missed opportunity if such by-products were wasted instead of reused and innovative, effective, and safe products. Therefore, the new FPR can be challenging to apply within European countries.

2.5.3. BBFs application between regulation

The research on waste processing is still running to produce safe and sustainable biofertilizers. The reason behind the development is that the long-term use of bio-waste-based substrate leads to even more excellent soil chemical or microbial contamination, such as microplastics, nanoparticles, or active compounds of pharmaceuticals (Kacprzak et al., 2022). The Regulation (EU) 2019/1009 represents an important step of the EU circular economy action plan with its aim to promote the production of fertilizers with reduced cadmium content. However, soil cadmium reduction is questionable and needs to complement policy tools to protect and conserve agricultural soil health, such as EU Soil Framework Directive (SFD) (Marini et al., 2020).

The problems can be a paradox since the situation could bring out business opportunities for producer companies due to the decentralization of biogas plants. Waste management can be done locally to reduce the transportation cost from waste collection to waste treatment. As a result, BBFs as source nutrients for plants is also a profitable business in the future.

Farmers already used manures in their farming as part of bio-based fertilizers. Across all regions, more than 90% of farmers admitted to using manure on their crops, with nearly half claiming to have encountered macronutrient or micronutrient deficiencies (Tur-Cardona et al., 2018). Therefore, BBFs' production should fulfill similar characteristics with conventional fertilizers to be accepted in society. Moreover, it will benefit not only concentrated products but also the price and the fast-release nutrients.

3. MATERIALS AND METHODS

3.1. Methods for field experiments

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.

3.1.1. Experimental sites and weather conditions

A field experiment was established in Nikla, Hungary (46.736° S, 17.238° E) 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 main focus, the experimental field with a low plant available P content was chosen in order to show effects of BBF treatments on the yield. The soil texture was loamy sand with 28 mg kg^{-1} Olsen P or 33 mg kg^{-1} based on ammonium-lactate soluble P method.

Climate normals were calculated based on the 1901–2000 average. 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 5. 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.

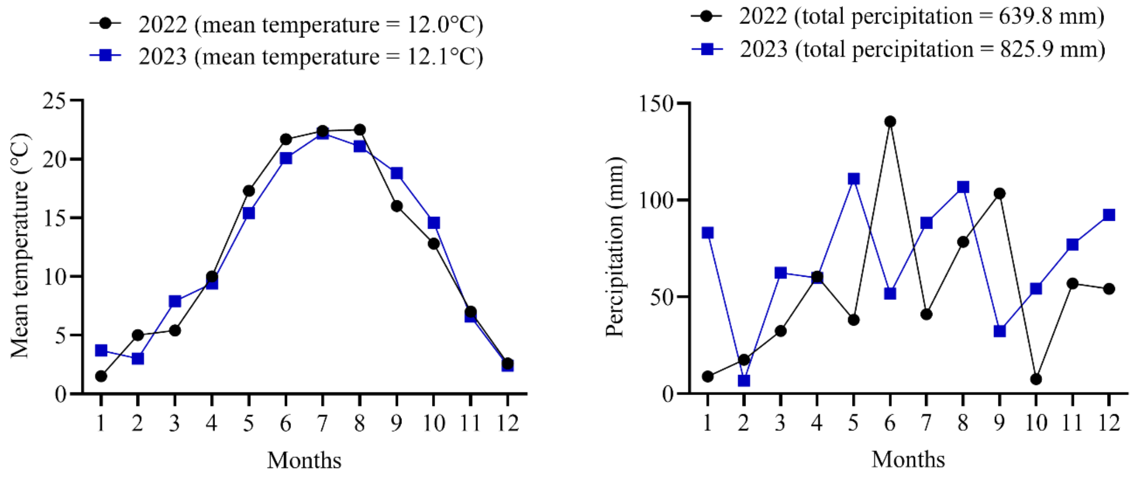


Figure 5. Weather data from Keszthely agrometeorological research station, Hungary (around 41 km far away from the experimental site).

3.1.2. Soil collection and characterization

At the beginning of the experiment (March 2022), the initial soil sample (before fertilization) from field experiment site was collected compositely from the top 0 to 20 cm. After collection, soils were air-dried and sieved to 2 mm and thoroughly homogenised to be analyzed for basic soil characteristics (Table 4). 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 4. 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	6 g/kg

3.1.3. Crop and soil management

The experiment was started by soil preparation, treatments application, seedling, sampling, and harvesting (Table 5). 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 5. 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.
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.

3.1.4. 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 (**see the appendices 8.3**).

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.

3.1.5. 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 6. 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 6. 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 (Table 7 and Fig. 6). 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).

Table 7. List of P-BBFs tested in the field experiments

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

PFC : product function category according to EU (2019)/1009

CMC : component material categories according to EU (2019)/1009

1 A-1 : solid organic fertilizers: ≥ 15% C organic

1 C-1 : solid inorganic macronutrients fertilizers

CMC 4 : fresh crop digestates

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

Figure 6. Different types of bio-based fertilizers used in the field experiment.

3.1.6. 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. Aboveground 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).

3.1.7. 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 8.

Table 8. 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 9 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 9. 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)

Parameter	Unit	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

3.1.8. 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.

3.2. 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.

4. RESULTS AND DISCUSSIONS

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

4.1.1 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. 7). 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 7. Weed infestation observed in the maize field before mechanical control

An analysis of variance was performed to determine the effect of BBFs on growth and yield of maize. There were no significant differences among parameters observed (Table 10). In this case, BBFs show no effect on the plants, as is also the case with mineral P fertilizer and the control (without fertilizer).

Table 10. Summary of ANOVA results in the first-year maize trial (2022)

Parameter	Treatment	Coefficient of variation (%)
Plant sampling at seven weeks after sowing (elongation stage)		
Plant height per plant (cm)	ns	10.26
Number of leaves per plant	ns	9.09
Stem diameter per plant (cm)	ns	7.11
Total leaf area per plant (m^2)	ns	18.10
Soil and plant sampling at harvesting period		
Soil P content (mg kg^{-1})	ns	24.77
Fresh biomass of maize (kg ha^{-1})	ns	21.92
Dry biomass of maize (kg ha^{-1})	ns	21.88
Phosporus uptake (kg ha^{-1})	ns	33.75
Nitrogen uptake (kg ha^{-1})	ns	31.98

ns means non-significant difference

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 11). 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 11. 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

Treatment	Plant height per plant (cm)	Number of leaves per plant	Stem diameter per plant (cm)	Total leaf area per plant (m^2)
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. 8).

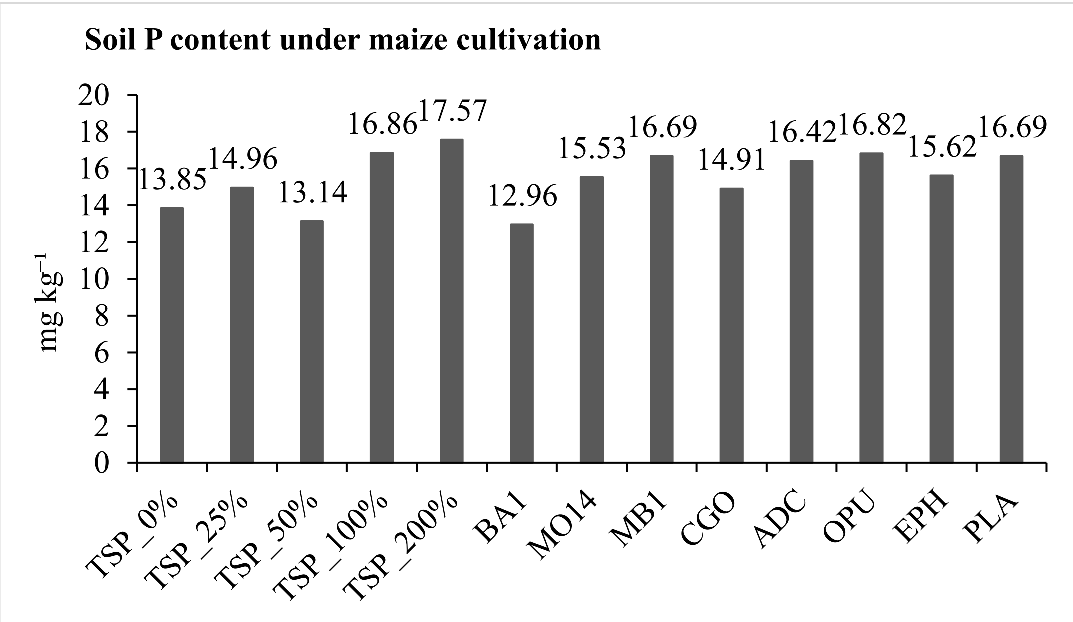


Figure 8. Effects of bio-based fertilizers on olsen P in maize fields at Nikla, Hungary, during the first experimental year (2022)

Although numerical variations in P uptake were observed among treatments (Fig. 9), 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.

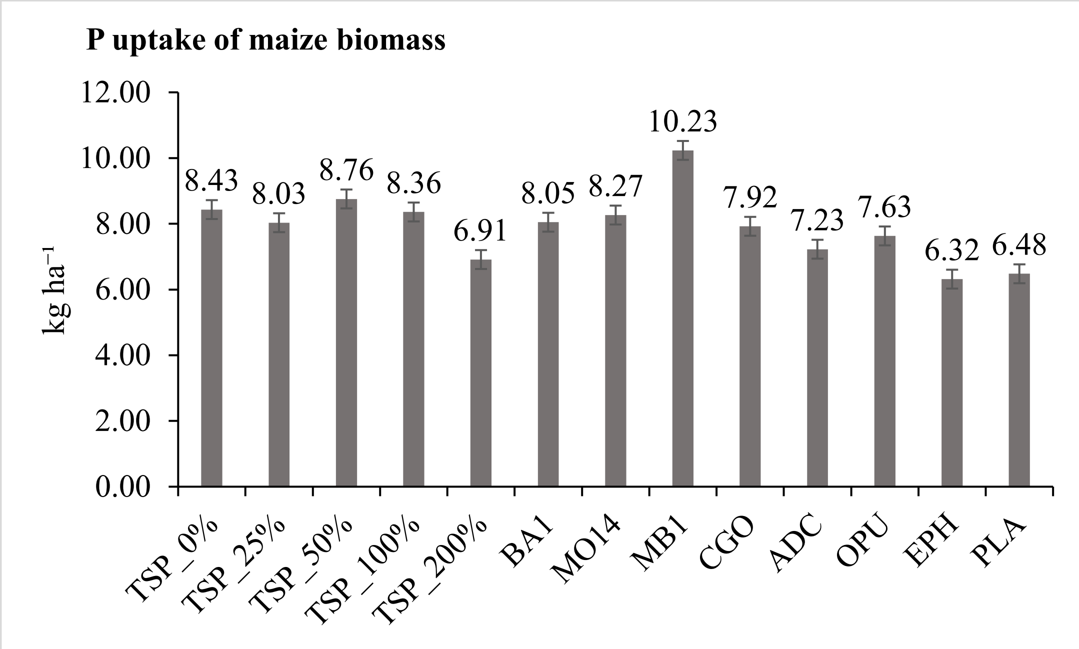


Figure 9. Effects of bio-based fertilizers on P uptake of maize biomass at Nikla, Hungary, during the first experimental year (2022)

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. 10). Meat bone meal (MB1) also resulted in higher stem diameter and leaf area (Table 11), which was consistent with its higher Olsen P levels (Fig. 8) and the greatest total P and N uptake by maize biomass (Figs. 9 and 10). 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

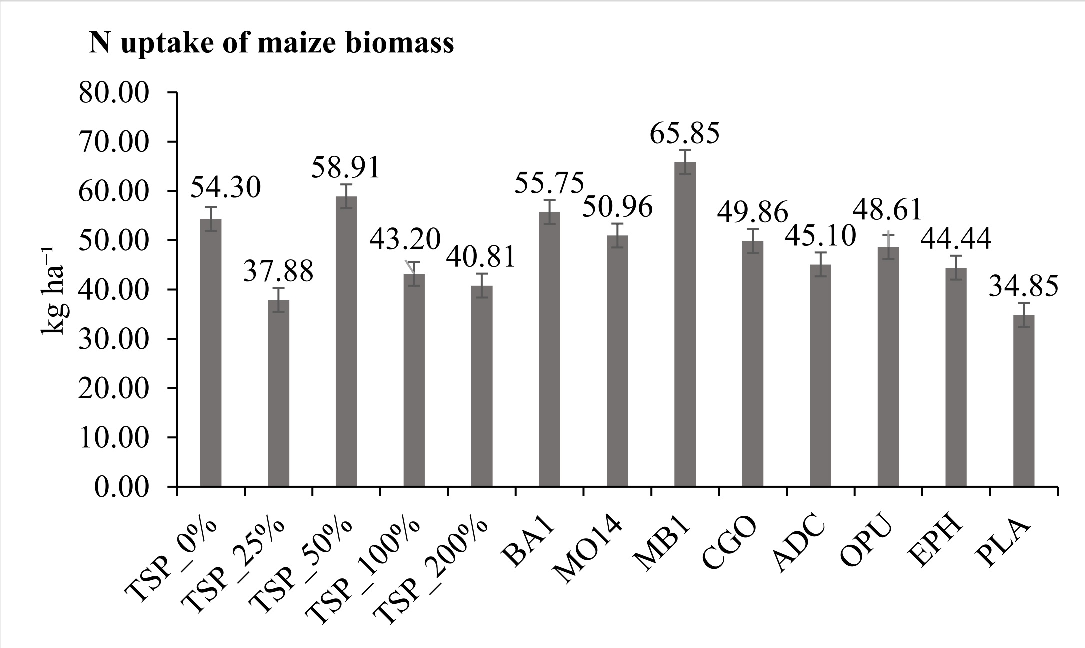


Figure 10. Effects of bio-based fertilizers on N uptake of maize biomass at Nikla, Hungary, during the first experimental year (2022)

Lower P and N uptake values for several treatments may indicate weed competition, drought stress, or imperfect nutrient availability, consistent with the results from fresh and dried weight of maize biomass (Table 12). Even, there was no phosphorus-response curve observed for either fresh or dry weight of maize above-ground biomass, like the results for soil P content. In this case, weed infestation may have contributed to reduced nutrient uptake due to competition with the maize plants, resulting in no detectable differences between the fertilized treatments and the unfertilized control. Linares et al. (2008) showed that weeds can pre-empt soil nutrients through competitive uptake, reducing nutrient availability to crops and potentially obscuring fertilizer responses. Nevertheless, the ADC treatment showed the highest values for both parameters compared with the other bio-based fertilizers.

Table 12. Effects of BBF application on above-ground biomass (fresh and dry weight) of maize at Nikla, Hungary, during the first experimental year (2022)

Treatment	Fresh weight of biomass (kg ha^{-1})	Dried weight of biomass (kg ha^{-1})
TSP_0%	5521.25 ± 1110.30	4830.00 ± 999.80
TSP_25%	5116.50 ± 851.54	4515.00 ± 717.29
TSP_50%	5477.00 ± 1823.92	4830.00 ± 1626.65
TSP_100%	5016.00 ± 1849.91	4410.00 ± 1626.65
TSP_200%	4781.00 ± 1242.06	4200.00 ± 1084.44
BA1	4434.75 ± 1000.22	3885.00 ± 865.85
MO14	4763.50 ± 1154.69	4200.00 ± 1028.79
MB1	4656.75 ± 446.75	4095.00 ± 402.12
CGO	4412.00 ± 990.21	3885.00 ± 865.85
ADC	5377.00 ± 1940.45	4725.00 ± 1693.07
OPU	4197.00 ± 839.27	3675.00 ± 717.29
EPH	4453.50 ± 1209.16	3885.00 ± 1050.00
PLA	4290.00 ± 901.50	3780.00 ± 766.81

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

4.1.2 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. 11). 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.

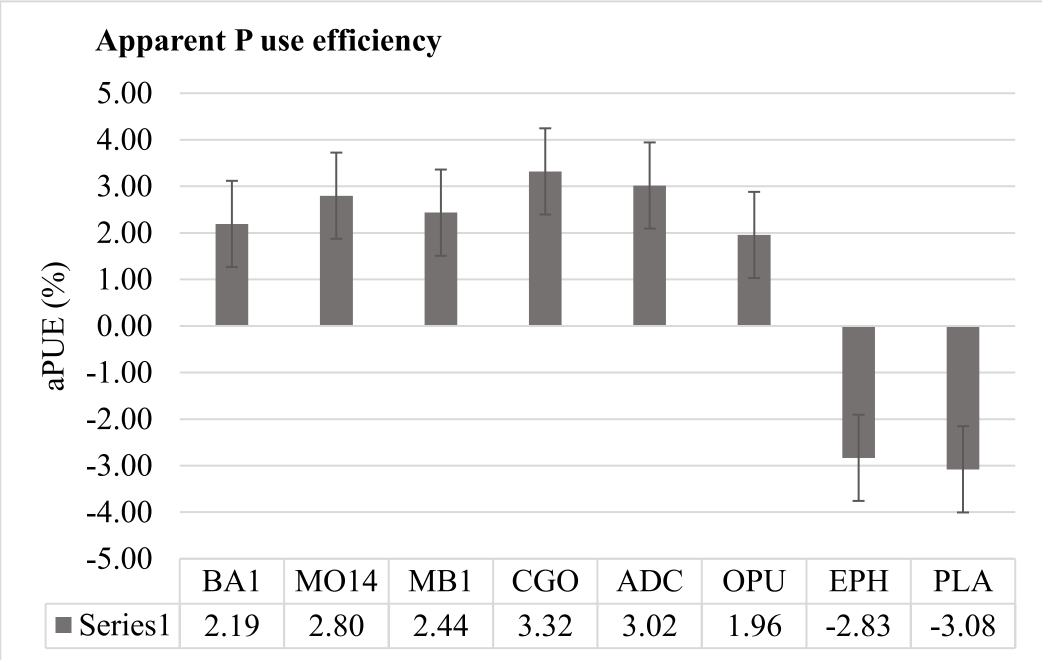


Figure 11. Apparent P use efficiency (aPUE) of bio-based fertilizers at Nikla, Hungary, during the first experimental year (2022)

Mineral replacement values (MRV) also varied widely among the tested recycled P materials (Fig. 12). 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.

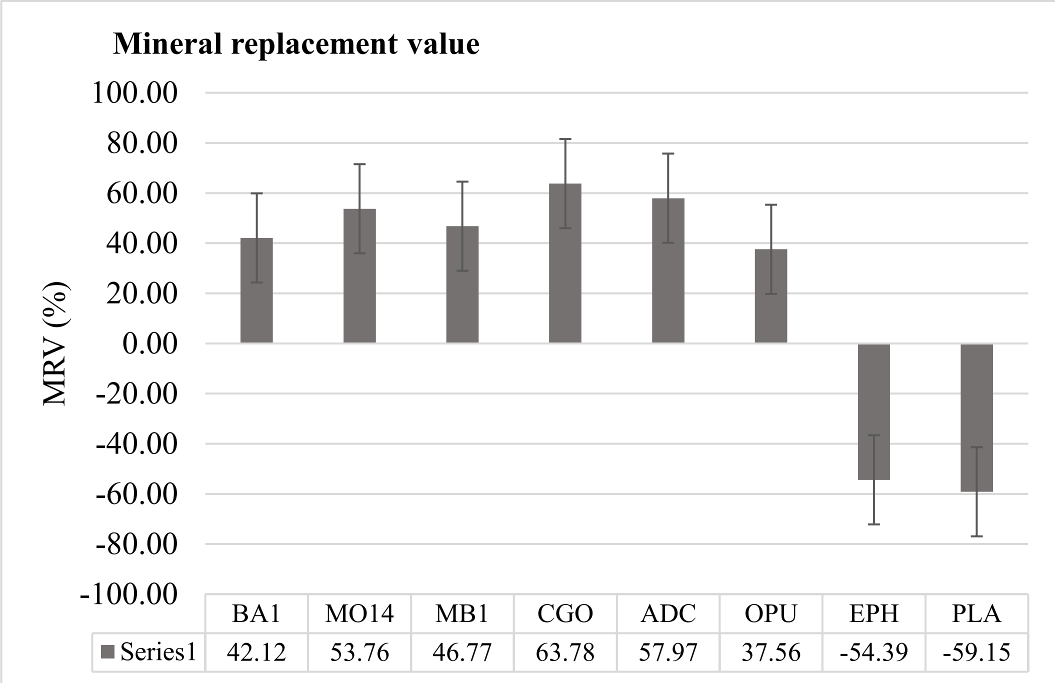


Figure 12. Mineral replacement value (MRV) of bio-based fertilizers at Nikla, Hungary, during the first experimental year (2022)

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).

4.1.3 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. 13). 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 13. Field preparation for winter wheat experiment in the second year.

Fertilization with BBFs and conventional fertilizers had no significant effect on almost all parameters, except on P concentration of grain (Table 13). In the analysis of the series of trials, fertilization was close to being a significant factor (around p= 0.0509) for some parameters, such as N concentration of grain (residual), P concentration of straw (fertilized), and total P uptake (fertilized).

Table 13. Summary of ANOVA results in the first-year winter wheat trial (2023)

Parameter	Treatment		Coefficient of variation (%)	
	Fertilized	Residual	Fertilized	Residual
Fresh grain weight of winter wheat (kg ha^{-1})	ns	ns	7.35	8.67
Fresh biomass of winter wheat (kg ha^{-1})	ns	ns	19.85	22.20
Grain yield of winter wheat (kg ha^{-1})	ns	ns	7.34	8.67
Dry biomass of winter wheat (kg ha^{-1})	ns	ns	20.03	22.35
P concentration of grain (%)	*	ns	9.60	11.85
P concentration of straw (%)	*	ns	7.43	30.00
N concentration of grain (%)	ns	*	6.79	6.00

Parameter	Treatment		Coefficient of variation (%)	
	Fertilized	Residual	Fertilized	Residual
N concentration of straw (%)	ns	ns	20.11	24.70
Soil P content (mg kg⁻¹)	ns	ns	23.75	11.30
Total P uptake	*	ns	6.07	18.67
Total N uptake	ns	ns	12.56	14.11

ns means non-significant difference
* Represents significant level at 5%

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. 14). 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.

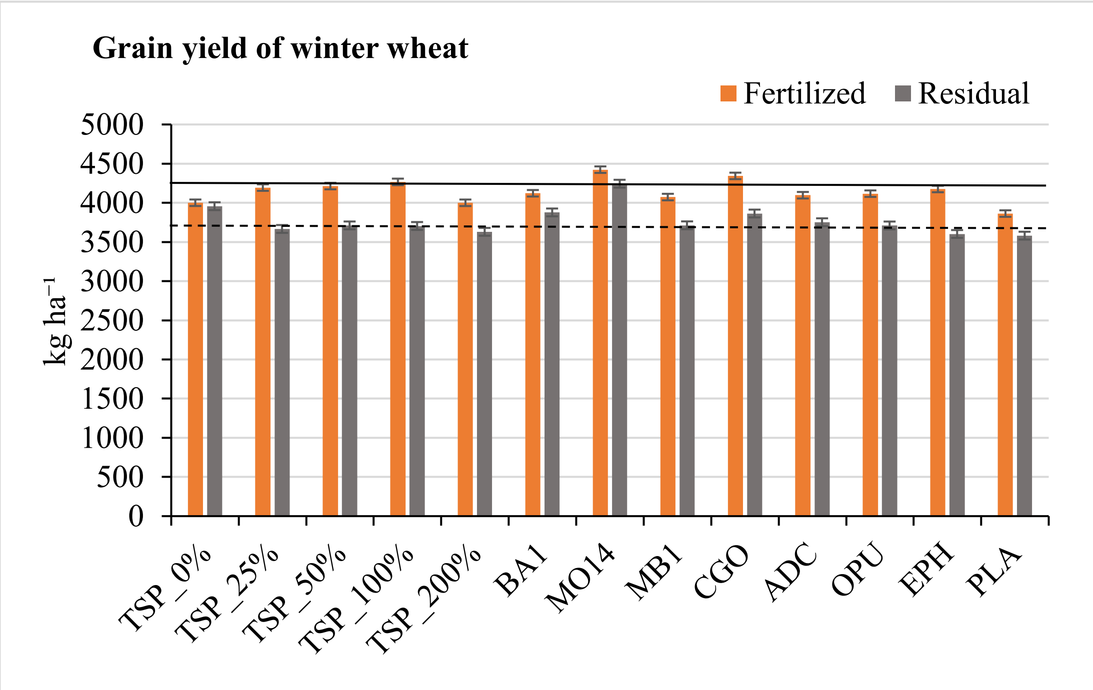


Figure 14. Grain yield of winter wheat (kg ha⁻¹) at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

Grain yield and fresh grain weight of winter wheat show a strong positive relationship across all treatments (Fig. 14 and 15). Treatments that produced higher fresh grain weight consistently resulted in higher grain yield, while treatments with lower fresh grain weight also exhibited reduced grain yield. In addition, both parameters responded similarly to mineral phosphorus rates, with increases up to the standard TSP 100% rate followed by no further improvement or slight declines at the TSP 200% rate.

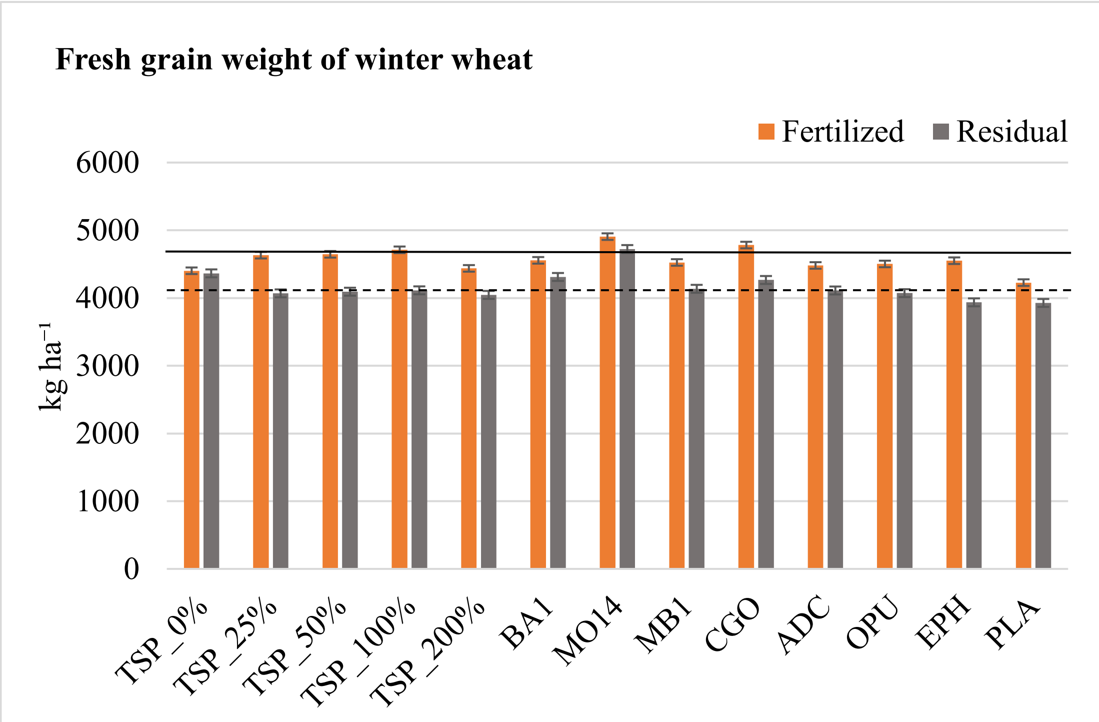


Figure 15. Fresh grain weight of winter wheat (kg ha^{-1}) at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

Among the bio-based fertilizers, MO14 and CGO also produced some of the highest fresh grain weights under fertilized conditions, while PLA consistently showed the lowest values under both fertilized and residual treatments. This experiment showed almost the same results as the trial conducted in the first year of maize cultivation (see Sections 4.1.1 and 4.1.2). Across all treatments, fertilized plots produced higher fresh grain weight than residual plots, with an average reduction of approximately 300–500 kg ha^{-1} observed under residual conditions. Despite these numerical trends, the overlap among treatments suggests that most bio-based fertilizers achieved fresh grain weights broadly comparable to the standard TSP 100% rate.

Figure 16 showed that fresh biomass of winter wheat exhibited closely related response patterns to the result of fresh grain weight (Fig. 15), indicating that vegetative growth largely determined final grain production. Among the bio-based fertilizers, treatments such as MO14, ADC, EPH, and PLA that produced higher fresh biomass under fertilized conditions also tended to result in higher fresh grain weight. Phosphorus from sewage sludge ash (ADC) and vegetable by-products (MO14) had tendency to have high result because Kominko et al., (2021, 2022) stated that formulation of organo-conventional fertilizer based on sewage sludge contained over 20% organic matter and it had high agronomic efficiency, which was confirmed in the pot trials due to their essential nutrient contained.

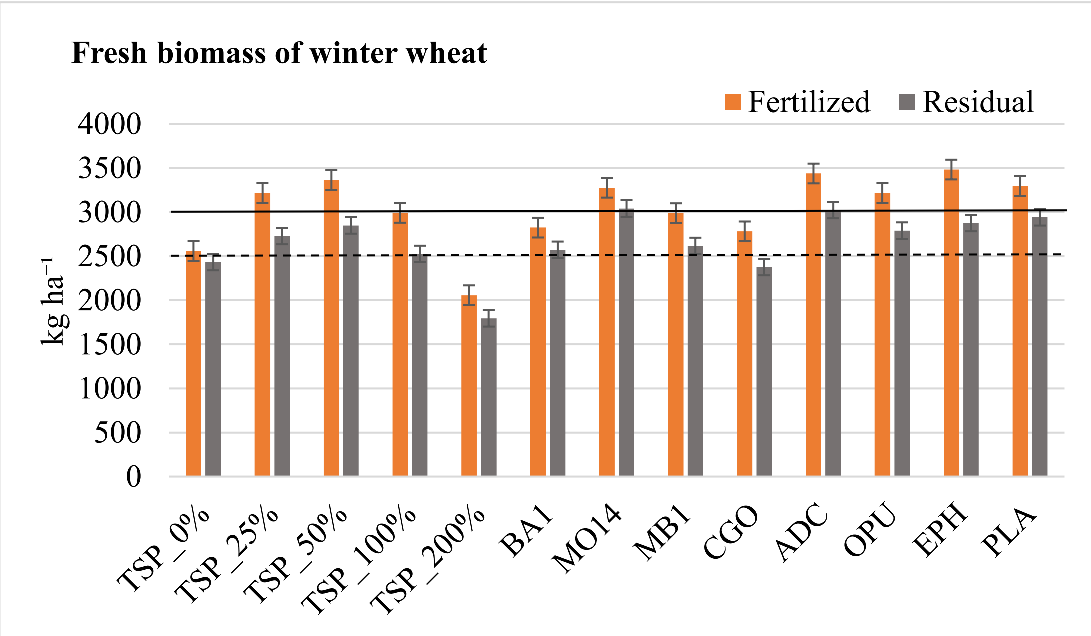


Figure 16. Fresh biomass of winter wheat (kg ha^{-1}) at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

Across all treatments, fertilized plots consistently produce higher biomass and grain weight than residual plots, confirming the greater importance of current-season phosphorus availability for both vegetative and reproductive growth. This result is in line with Hao et al. (2024), P-fertilized plots produced 18-22 % higher aboveground biomass than unfertilized controls, with enhanced P uptake at maturity under maize cultivation.

Winter wheat biomass (dried) was consistently higher under fertilized than residual conditions across all treatments (Fig. 17). There was also a positive curve P response in TSP rate, but it declined at the 200% rate, indicating a possible negative effect of excessive fertilization. Among the BBFs treatments, ADC, EPH, and PLA produced the highest biomass yields. Residual treatments resulted in lower biomass overall, demonstrating that fresh fertilizer application was more effective than residual nutrient supply.

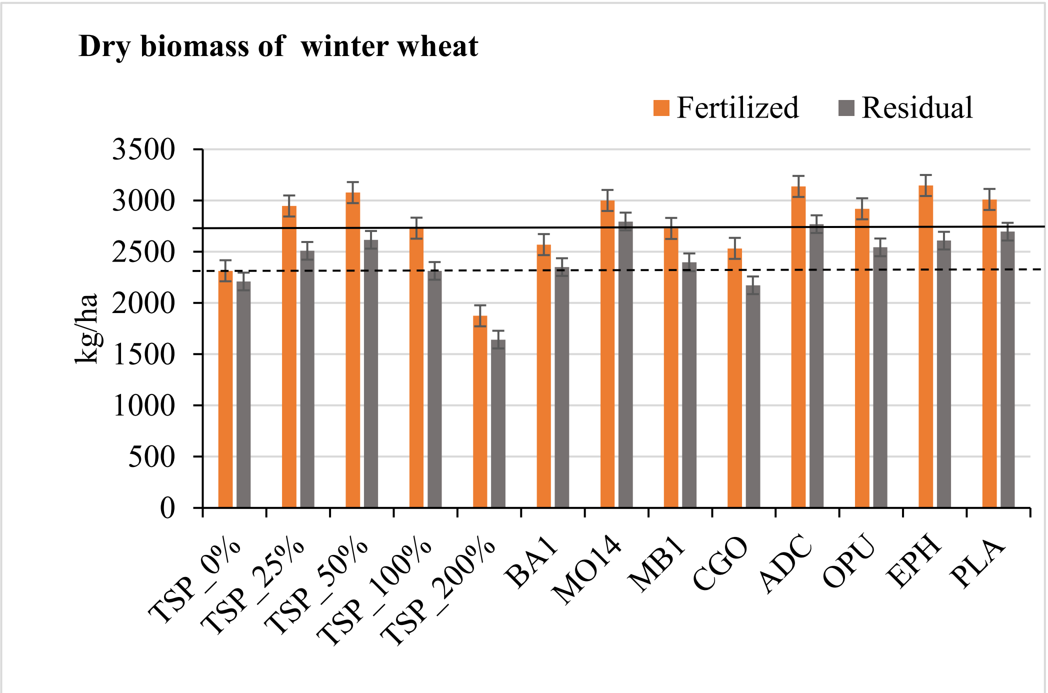


Figure 17. Dry biomass of winter wheat (kg ha^{-1}) at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

There was a positive curve P response in conventional fertilizer, showing responsive results on fertilization (Table 14). 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. 14) 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 14. 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.

Phosphorus (P) concentration on biomass of winter wheat under different fertilization treatments ranged from 0.24 to 0.34% (Table 15). The highest mean P concentration was observed in CGO (0.34%), surpassing the TSP_100% reference treatment (0.32%). However, based on Tukey's test at the 5% significance level, all fertilization treatments were not significantly different from each other, as indicated by the same letter notation.

Table 15. Effect of bio-based fertilizers on biomass phosphorus concentration of winter wheat at Nikla, Hungary, during the second experimental year (2023)

Fertilization treatment	P concentration (%)	Residual treatment	P concentration (%)
TSP_0%	0.24 a ± 0.02	TSP_0%	0.25 ± 0.05
TSP_25%	0.25 a ± 0.02	TSP_25%	0.33 ± 0.05
TSP_50%	0.25 a ± 0.01	TSP_50%	0.26 ± 0.04
TSP_100%	0.32 a ± 0.07	TSP_100%	0.30 ± 0.04
TSP_200%	0.29 a ± 0.02	TSP_200%	0.26 ± 0.02
BA1	0.26 a ± 0.03	BA1	0.31 ± 0.04
MO14	0.26 a ± 0.05	MO14	0.25 ± 0.08
MB1	0.31 a ± 0.02	MB1	0.27 ± 0.05
CGO	0.34 a ± 0.04	CGO	0.31 ± 0.02
ADC	0.29 a ± 0.06	ADC	0.26 ± 0.02
OPU	0.29 a ± 0.05	OPU	0.26 ± 0.06
EPH	0.32 a ± 0.05	EPH	0.31 ± 0.003
PLA	0.27 a ± 0.05	PLA	0.26 ± 0.05

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

Figure 18 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.

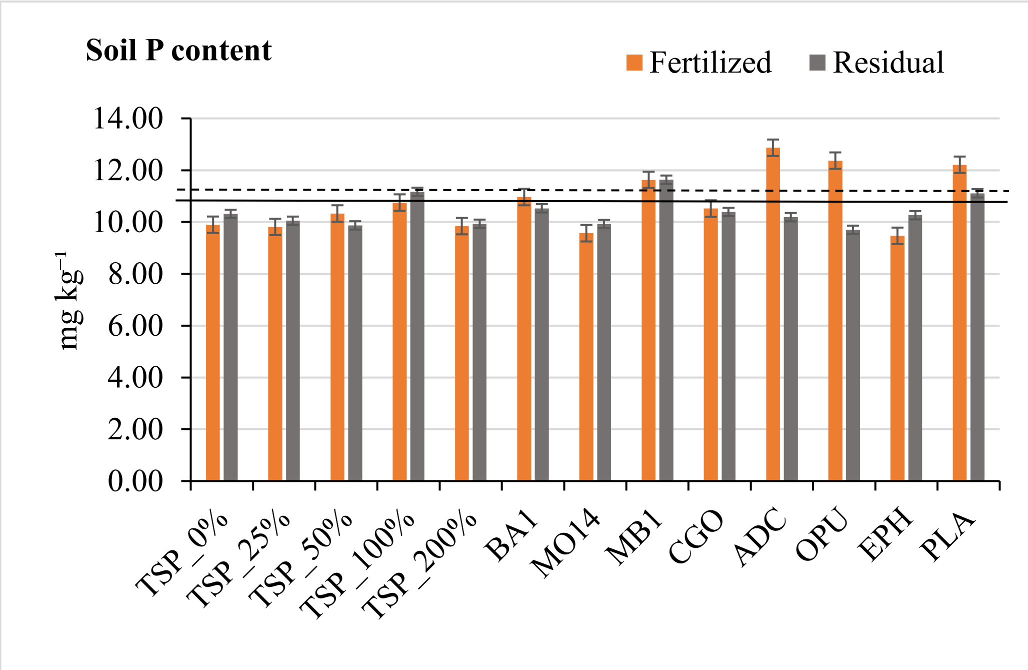


Figure 18. Soil P content (mg kg^{-1}) of winter wheat at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

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. 19). 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.

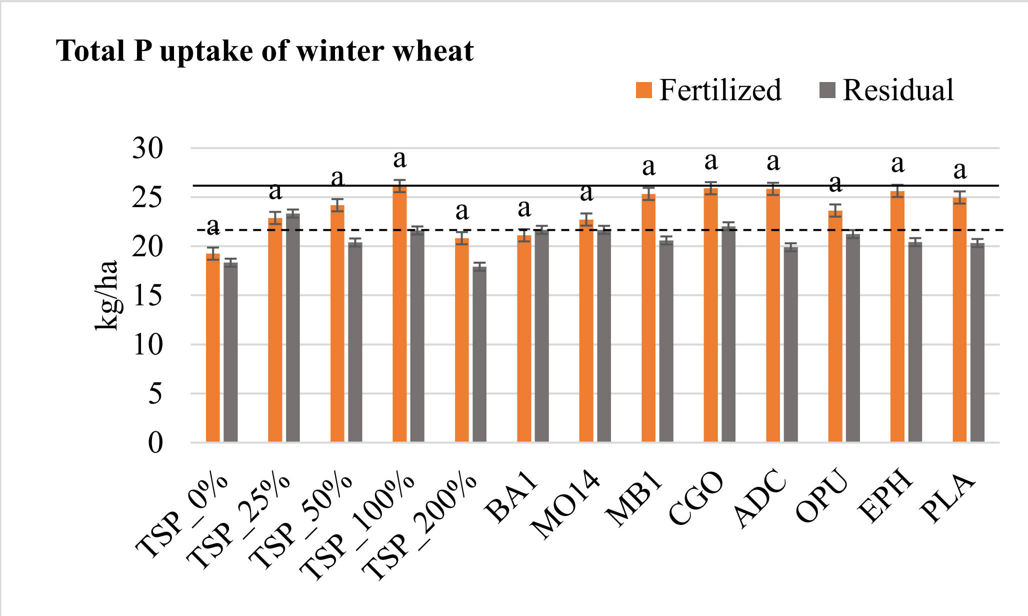


Figure 19. Total P uptake (kg ha^{-1}) of winter wheat at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

Grain yield and total P uptake responses showed contrasting patterns among fertilization treatments. Although MO14 produced one of the highest grain yields (Fig. 14), total P uptake did not increase proportionally and remained statistically comparable to other fertilized treatments (Fig. 19). 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. 19), 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. 20). 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.

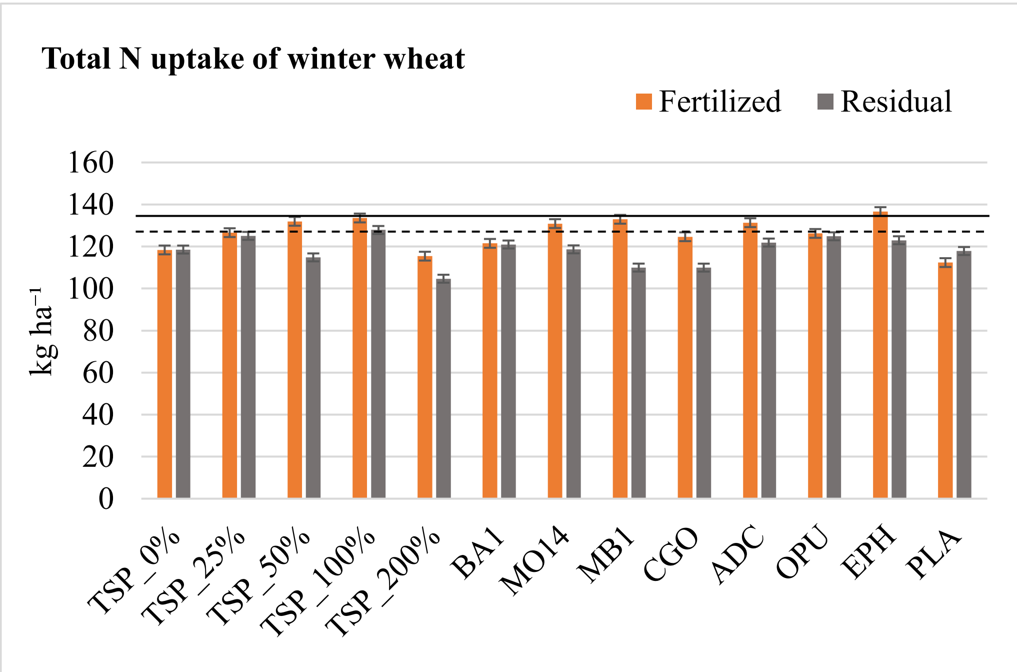


Figure 20. Total N uptake (kg ha^{-1}) of winter wheat at Nikla, Hungary, during the second experimental year (2023). Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

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 16.). 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 16. 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).

Similar with grain nitrogen concentrations, biomass nitrogen concentrations of winter wheat also showed limited numerical variation among fertilization and residual treatments, and the observed differences were not statistically significant (Table 17). The consistency between biomass and grain N responses indicates that neither the mineral P rates nor the different bio-based fertilizers significantly altered plant N concentration or N partitioning between vegetative tissues and grain in the second year. Although some treatments showed slightly higher residual values for both biomass and grain N concentrations, these trends were not statistically supported and likely reflect natural field variability rather than true treatment effects.

Table 17. Effects of bio-based fertilizers on biomass nitrogen concentration of winter wheat at Nikla, Hungary, during the second experimental year (2023)

Fertilization treatment	N concentration (%)	Residual treatment	N concentration (%)
TSP_0%	1.19 ± 0.22	TSP_0%	1.14 ± 0.24
TSP_25%	1.16 ± 0.16	TSP_25%	1.43 ± 0.56
TSP_50%	1.18 ± 0.12	TSP_50%	1.25 ± 0.28
TSP_100%	1.14 ± 0.17	TSP_100%	1.56 ± 0.18
TSP_200%	1.22 ± 0.36	TSP_200%	1.34 ± 0.29
BA1	1.23 ± 0.29	BA1	1.28 ± 0.18
MO14	1.11 ± 0.40	MO14	0.91 ± 0.30
MB1	1.47 ± 0.40	MB1	1.01 ± 0.22
CGO	1.21 ± 0.27	CGO	1.23 ± 0.29
ADC	1.16 ± 0.17	ADC	1.45 ± 0.67
OPU	1.23 ± 0.34	OPU	1.33 ± 0.45
EPH	1.09 ± 0.23	EPH	1.48 ± 0.06
PLA	0.81 ± 0.09	PLA	1.35 ± 0.16

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

4.1.4 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. 21), 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.

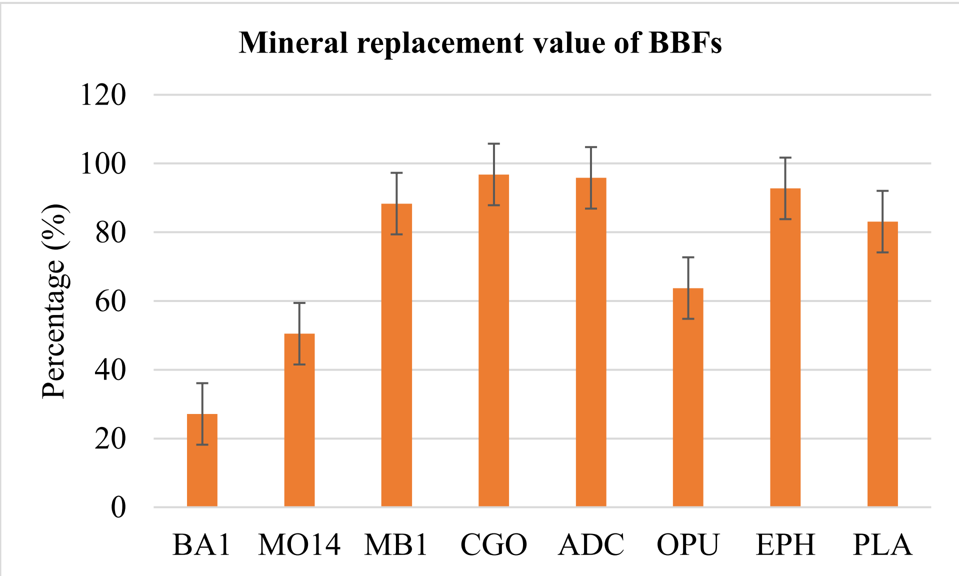


Figure 21. Mineral replacement values (MRV) of bio-based fertilizers (BBFs) for the fertilized subplot at Nikla, Hungary, during the second experimental year (2023).

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. 23).

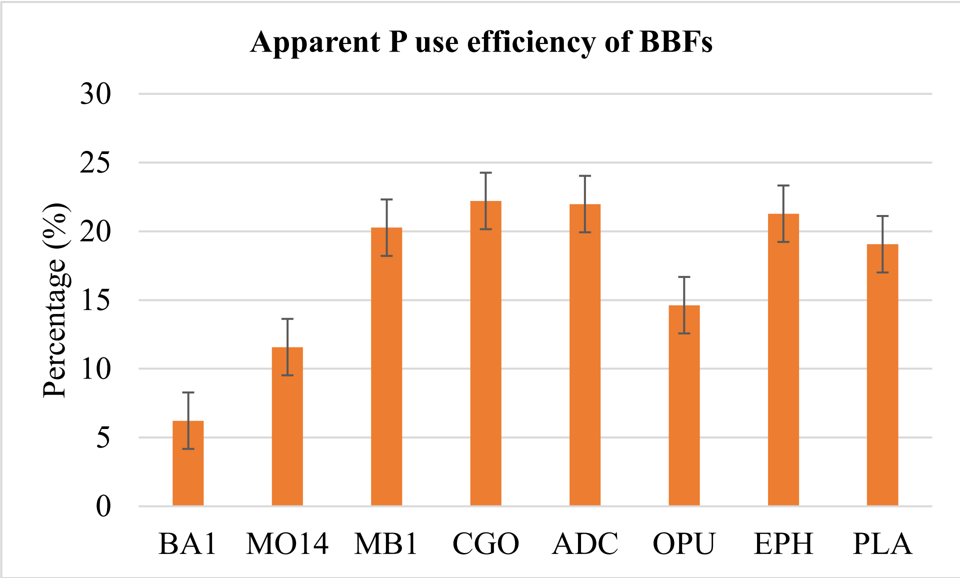


Figure 22. Apparent P use efficiency (aPUE) of the BBFs for the fertilized subplot at Nikla, Hungary, during the second experimental year (2023).

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.

Overall, the harvest index of winter wheat varied moderately among the different phosphorus treatments, with values generally ranging between about 60 and 77% (Fig. 23). 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.

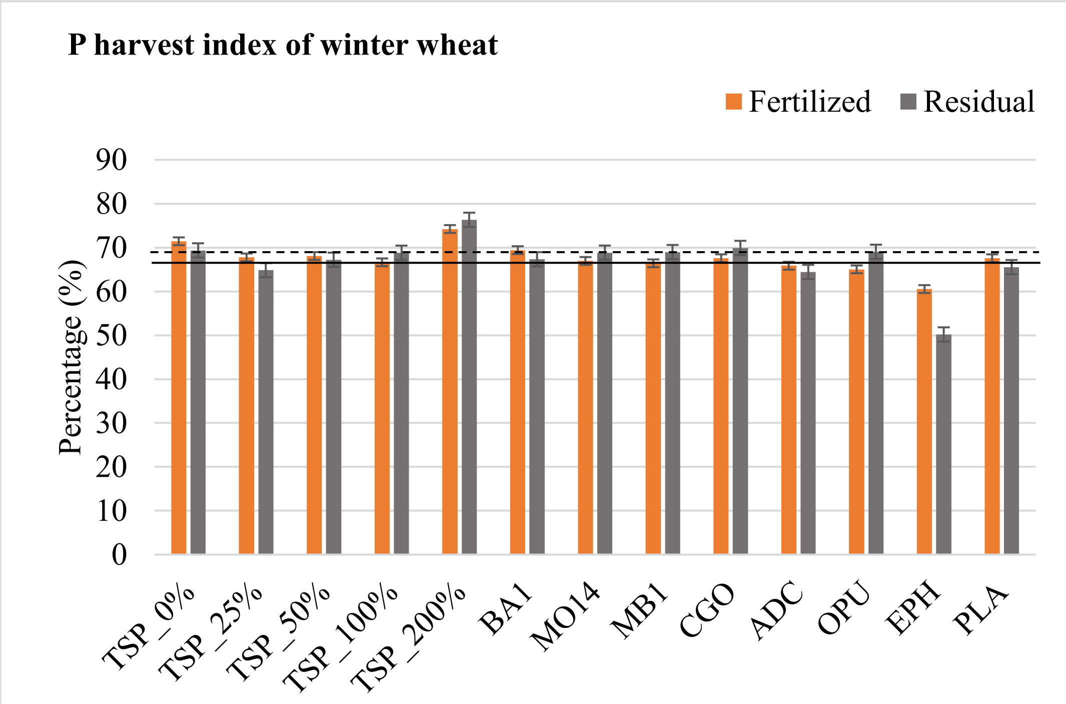


Figure 23. P harvest index (PHI) of winter wheat in the second year of the experiment. Black lines indicate the yield level of the TSP 100 % reference for fertilized treatment, while dashed lines show the yield level of the TSP 100 % reference for residual treatment.

4.2. 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. We will never make a movement without a new step. Research about bio-based fertilizers is targeted to meet the requirement set for the BBFs by farmers and society at large. 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. (Chojnacka et al., 2020) suggested that incentives are needed for wastes valorization and fines for making use of nonrenewable raw materials. Ultimately, profitability will be questionable at the beginning of starting the business (short-term profit).

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.

There are still many steps to reach the goals of BBFs implementation to support the transition towards circular economy by enhancing the use of nutrient-rich-side streams. Future research is going to be done from lab to field scale, such as validation trial and the technology readiness levels (TRLs). Then, life cycle sustainability assessment is needed to evaluate the potential benefits and consequences of BBFs as compensation of conventional fertilizers through LCC (techno-economical), LCA (environmental), and S-LCA (socio-economical). The environmental impact of a bio-based fertilizer will depend on the type of waste in question, coupled with the treatment technology and utilization of the outputs as a result (Jensen et al., 2020). Furthermore, the use of BBFs needs to be observed not only in the short time but also in the long term (15–20 years) to determine the environmental impact and to determine safe doses of BBFs (Dubis et al., 2020).

Examining regulations and certification of the implementation of BBF usage at a large community is also needed. To get social acceptance, the government and stakeholders could monitor via policy involving actors of value chain, including livestock and agriculture sector, chemical industry, technology provider, and society. Pressure from governmental legislation was identified as the key stimulant of technology adoption for BBFs production, such as the promotion of manure treatment must be economically appealing to attract new adopters (long-term financial support schemes and marketing strategies) (Hou et al., 2018).

4.3. 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 18) 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 18. 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 and level of usage from farmers
Hijbeek et al., 2019	There are four types of waste-based fertilizers tested in this study (straw incorporation, green manure or cover crops,	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

Contribution	Model of implementation	Challenges	Recommendations
	compost, and farmyard manure)		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

4.4. 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.

4.5. 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. 24. The future policy could be improved by tackling its blind spots. There are two key stakeholders to be considered: producers and end users (farmers).

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).

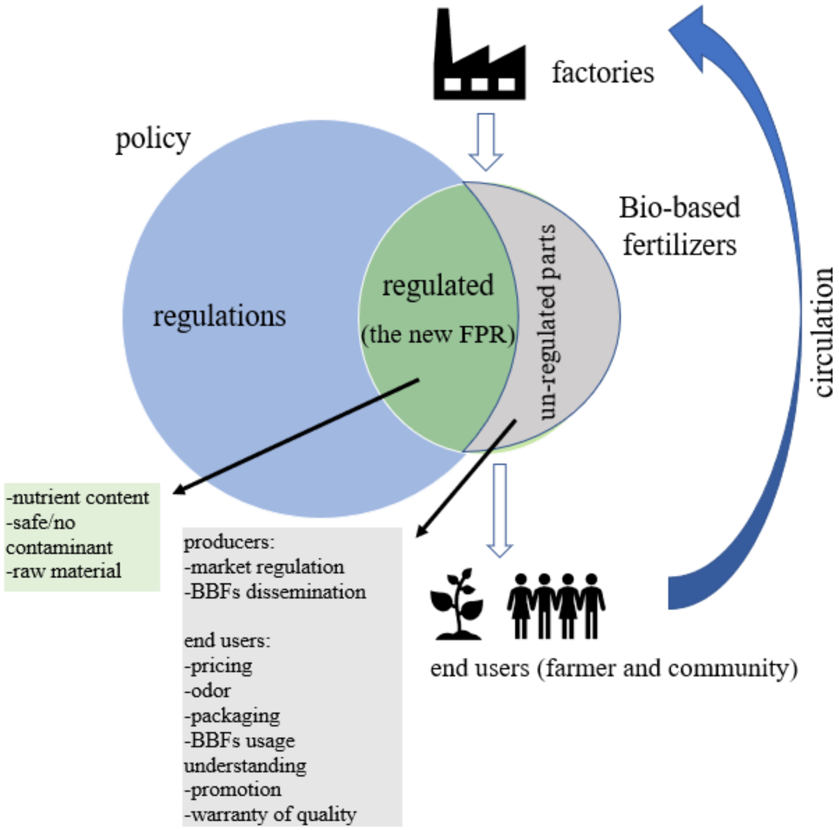


Figure 24. The new FPR in relation to the domains related to BBFs.

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).

4.6. Implications of Bio-Based Fertilizers for Fertilizer Policy to Support Circular Economy

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. 25. 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).

Figure 25. The role of Policies and Facilities to support stakeholders on BBFs implementation.

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.

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).

5. CONCLUSIONS AND RECOMMENDATIONS

The conclusion of the study is summarized in this chapter. This chapter consists of two main sections. An overview of the findings and their importance for theory and practice are presented in the first section, while recommendations are provided in the second section.

5.1. Conclusions

This study evaluated the agronomic, environmental, and policy-related aspects of bio-based fertilizers (BBFs) as phosphorus (P) sources in organically cultivated loamy sand acidic soil in Hungary, with the aim of addressing their effectiveness, efficiency, and broader role within a circular economy framework.

Bio-based fertilizers (BBFs) can function as effective phosphorus (P) sources in organically cultivated loamy sand acidic soils in Hungary. When applied at equivalent total P rates, most BBFs performed comparably to mineral P fertilizers in terms of soil P content, P availability, and plant P uptake when evaluated on a yearly basis. Although differences were not statistically significant, increases in both soil P content and total P uptake were generally observed in the second year, particularly in fertilized treatments. These results indicate a gradual improvement in P availability over time, while also showing that clear residual fertilizer effects were not evident under the study conditions.

The agronomic efficiency of BBFs as P sources for plants was found to be comparable to that of mineral fertilizers in organic farming systems. While agronomic performance varied among individual BBFs, these differences were not statistically significant. Notably, agronomic efficiency was higher in the second year than in the first year, reflecting the slow-release characteristics and cumulative effects of BBFs. This finding highlights the suitability of BBFs for sustained nutrient supply in sandy, acidic soils managed under organic production systems in Hungary.

Beyond field-level performance, the results support the potential of BBFs to partially or fully replace conventional mineral P fertilizers, thereby contributing to the principles of the circular economy. Given that the P demand of European croplands is generally lower than current fertilizer recommendations, recycled P products derived from bio-waste streams could substantially meet crop requirements. The study confirms that BBFs can simultaneously enhance nutrient recycling, reduce dependence on finite mineral P resources, and support bio-waste management, reinforcing their role as future-oriented agricultural inputs within the EU bio-based economy.

The study also emphasizes the importance of supportive policies and regulatory frameworks in enabling the wider adoption of BBFs. Although recent EU initiatives, such as the Fertilising Products Regulation (FPR), represent significant progress toward improving nutrient use efficiency and promoting recycled fertilizers, existing regulatory gaps remain, particularly regarding the inclusion of certain raw materials. Furthermore, challenges related to production technologies, product standardization, farmer acceptance, and socio-economic factors continue to constrain large-scale implementation. Addressing these barriers through targeted policy development, technological innovation, and stakeholder engagement will be essential to fully realize the potential of BBFs within sustainable agricultural systems.

5.2. Recommendations

Regarding the first challenge, the new FPR policy only focuses on raw materials based on Component Material Category (CMC) and Product Function Category (PFC) that ensure safety and effectiveness. Adding new materials (CMC) also generates confusion between CMC and PFC since contaminants are put in the CMC criteria, not in the PFC criteria. Thus, there is a necessity for action plans to comply criteria.

Other critical points of BBFs that should be mentioned in the legal requirements compared to conventional fertilizers are logistic issues, the characteristic of nutrient content, and prices. Also, the source of the waste stream needs to be more stable to produce in different batches. Several sectors, such as the chemical industry, technology providers, waste-management bodies, and society, especially farmers, should also be involved. At the same time, policymakers support clear regulatory actions to help and control the use of BBFs.

To sum up, the recommendation is to design BBFs as future fertilizers to tackle the problem of dependency on importing conventional fertilizers in EU countries through support from all parties. For instance, policy incentives to optimize wastes valorization and penalties to reduce the intensive use of non-renewable materials for fertilizer production could be alternative methods. However, the effectiveness of every action plan varies from country to country, depending on its socio-economic characteristic.

6. NEW SCIENTIFIC RESULTS

1. 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.
2. 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.
3. 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.
4. 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.
5. 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.

7. SUMMARY

Bio-based fertilizers (BBFs) aim to reduce the European Union's (EU) dependence on imported mineral fertilizers due to nonrenewable energy dependency and the accumulation that threatens environmental issues. By recycling and reusing nutrient-rich by-streams, BBFs present a promising shift toward sustainable agriculture. However, the implementation can be very complex, and the right policies must be delivered to optimize BBFs' production-consumption flows. Therefore, the study aimed to 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, and d) study the current policies and regulations and other initiatives related to the utilization of bio-based fertilizers in technology and socio-economic aspects.

Long-term P bioavailability was investigated in a field trial evaluating eight types of bio-based fertilizers (BBFs). The experiment was established in Nikla, Hungary, and conducted from May 2022 to July 2023 under different crop rotations. During the first year (May–October 2022), maize was cultivated, while winter wheat was grown during the second year (November 2022–July 2023). This research was carried out within the framework of the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 818309 (LEX4BIO). Therefore, all experimental methods followed the field trial protocol developed for Work Package 3 (WP3) of the LEX4BIO project, with minor adjustments made to accommodate local conditions.

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

The results highlight that BBFs can function as fully or partially effective replacement for commercial mineral P fertilizers, but the implementation is challenging due to its characteristics, such as the nutrient content, high transportation cost, farmer's acceptance, environmental risks (contamination), and policy frameworks. Moreover, in the level of field experiment, most BBFs performed equally well as the mineral reference applied at the same total P level when looking at the years individually. The P content and agronomic P efficiency showed better results in the second-year experiment even though there was no significant difference. The accumulation and slow-release effects of bio-based fertilizers might contribute to the higher number of parameters observed.

Finally, the potency of BBFs as a future fertilizer in replacing chemical fertilizers also needs to be supported by legal frameworks. Considering the current policy, including the new fertilizing product regulation, it is still under development to comply with some appropriate laws and regulations for their implementation since the limitation to component material category and product function category govern the specific function of the product and the raw material utilization. Therefore, supportive policies are needed to facilitate their production, marketing, and use. Addressing barriers for BBF uptake requires collaborative efforts from policymakers, researchers, industry, stakeholders and farmers themselves.

8. APPENDICES

8.1. Bibliography

Arcas-Pilz, V., Rufí-Salís, M., Parada, F., Petit-Boix, A., Gabarrell, X., & Villalba, G. (2021). Recovered phosphorus for a more resilient urban agriculture: Assessment of the fertilizer potential of struvite in hydroponics. *Science of The Total Environment*, *799*, 149424. https://doi.org/10.1016/j.scitotenv.2021.149424

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

Borges, B. M. M. N., Abdala, D. B., Souza, M. F. de, Viglio, L. M., Coelho, M. J. A., Pavinato, P. S., & Franco, H. C. J. (2019). Organomineral phosphate fertilizer from sugarcane byproduct and its effects on soil phosphorus availability and sugarcane yield. *Geoderma*, *339*, 20–30. https://doi.org/10.1016/j.geoderma.2018.12.036

Bousek, J., Schöpp, T., Schwaiger, B., Lesueur, C., Fuchs, W., & Weissenbacher, N. (2018). Behaviour of doxycycline, oxytetracycline, tetracycline and flumequine during manure up-cycling for fertilizer production. *Journal of Environmental Management*, *223*, 545–553. https://doi.org/10.1016/j.jenvman.2018.06.067

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

Chai, R., Ye, X., Ma, C., Wang, Q., Tu, R., Zhang, L., & Gao, H. (2019). Greenhouse gas emissions from synthetic nitrogen manufacture and fertilization for main upland crops in China. *Carbon Balance and Management*, *14*(1). https://doi.org/10.1186/s13021-019-0133-9

Cheong, J. C., Lee, J. T. E., Lim, J. W., Song, S., Tan, J. K. N., Chiam, Z. Y., Yap, K. Y., Lim, E. Y., Zhang, J., Tan, H. T. W., & Tong, Y. W. (2020). Closing the food waste loop: Food waste anaerobic digestate as fertilizer for the cultivation of the leafy vegetable, xiao bai cai (Brassica rapa). *Science of The Total Environment*, *715*, 136789. https://doi.org/10.1016/j.scitotenv.2020.136789

Chevillard, N., Bonadio, J., & Rossi, R. (2022). *Solar , Biodiversity , Land Use: Best Practice Guidelines*. https://api.solarpowereurope.org/uploads/4222_SPE_Biodiversity_report_03_mr_ba11900938.pdf?updated_at=2022-10-27T08:28:18.591Z

Chiew, Y. L., Spångberg, J., Baky, A., Hansson, P.-A., & Jönsson, H. (2015). Environmental impact of recycling digested food waste as a fertilizer in agriculture—A case study. *Resources, Conservation and Recycling*, *95*, 1–14. https://doi.org/10.1016/j.resconrec.2014.11.015

Chojnacka, K., Mikula, K., Skrzypczak, D., Izydorczyk, G., Gorazda, K., Kulczycka, J., Kominko, H., Moustakas, K., & Witek-Krowiak, A. (2022). Practical aspects of biowastes conversion to fertilizers. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-022-02477-2

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

Cui, N., Cai, M., Zhang, X., Abdelhafez, A. A., Zhou, L., Sun, H., Chen, G., Zou, G., & Zhou, S. (2020). Runoff loss of nitrogen and phosphorus from a rice paddy field in the east of China: Effects of long-term chemical N fertilizer and organic manure applications. *Global Ecology and Conservation*, *22*, e01011. https://doi.org/10.1016/j.gecco.2020.e01011

Dahlbergh, E., Sigurd Naess-Schmidt, Virtanen, L., Marcus, S., Salvo, M. Di, Pelkmans, J., Pozza, V. D., & Kubovicova, K. (2020). Legal obstacles in Member States to Single Market rules. In *European Parliament* (Issue November). https://www.europarl.europa.eu/RegData/etudes/STUD/2020/658189/IPOL_STU(2020)658189_EN.pdf

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.

Doña-Grimaldi, V. M., Palma, A., Ruiz-Montoya, M., Morales, E., & Díaz, M. J. (2019). Energetic valorization of MSW compost valorization by selecting the maturity conditions. *Journal of Environmental Management*, *238*, 153–158. https://doi.org/10.1016/J.JENVMAN.2019.02.125

Dubis, B., Jankowski, K. J., Załuski, D., & Sokólski, M. (2020). The effect of sewage sludge fertilization on the biomass yield of giant miscanthus and the energy balance of the production process. *Energy*, *206*, 118189. https://doi.org/10.1016/j.energy.2020.118189

Duquennoi, C., & Martinez, J. (2022). European Union's policymaking on sustainable waste management and circularity in agroecosystems: The potential for innovative interactions between science and decision-making. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.937802

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

Elshony, M., Farid, I., Alkamar, F., Abbas, M., & Abbas, H. (2019). Ameliorating a sandy soil using biochar and compost amendments and their implications as slow release fertilizers on plant growth. *Egyptian Journal of Soil Science*, *59*(4), 305–322. https://doi.org/10.21608/ejss.2019.12914.1276

EurEau. (2021). *Briefing Note Waste water treatment-sludge management*. The EurEau. https://www.eureau.org/resources/briefing-notes/5629-briefing-note-on-sludge-management/file

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

Foteinis, S., & Chatzisymeon, E. (2016). Life cycle assessment of organic versus conventional agriculture. A case study of lettuce cultivation in Greece. *Journal of Cleaner Production*, *112*, 2462–2471. https://doi.org/10.1016/j.jclepro.2015.09.075

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

Frišták, V., Pipíška, M., & Soja, G. (2018). Pyrolysis treatment of sewage sludge: A promising way to produce phosphorus fertilizer. *Journal of Cleaner Production*, *172*, 1772–1778. https://doi.org/10.1016/j.jclepro.2017.12.015

Garske, B., Stubenrauch, J., & Ekardt, F. (2020). Sustainable phosphorus management in European agricultural and environmental law. *Review of European, Comparative & International Environmental Law*, *29*(1), 107–117. https://doi.org/10.1111/reel.12318

Gontard, N., Sonesson, U., Birkved, M., Majone, M., Bolzonella, D., Celli, A., Angellier-Coussy, H., Jang, G.-W., Verniquet, A., Broeze, J., Schaer, B., Batista, A. P., & Sebok, A. (2018). A research challenge vision regarding management of agricultural waste in a circular bio-based economy. *Critical Reviews in Environmental Science and Technology*, *48*(6), 614–654. https://doi.org/10.1080/10643389.2018.1471957

Grillo, F., Piccoli, I., Furlanetto, I., Ragazzi, F., Obber, S., Bonato, T., Meneghetti, F., & Morari, F. (2021). Agro-Environmental Sustainability of Anaerobic Digestate Fractions in Intensive Cropping Systems: Insights Regarding the Nitrogen Use Efficiency and Crop Performance. *Agronomy*, *11*(4), 745. https://doi.org/10.3390/agronomy11040745

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

Guo, S., Pan, J., Zhai, L., Khoshnevisan, B., Wu, S., Wang, H., Yang, B., Liu, H., & Lei, B. (2020). The reactive nitrogen loss and GHG emissions from a maize system after a long-term livestock manure incorporation in the North China Plain. *Science of The Total Environment*, *720*, 137558. https://doi.org/10.1016/j.scitotenv.2020.137558

Guo, Z., Han, J., Li, J., Xu, Y., & Wang, X. (2019). Effects of long-term fertilization on soil organic carbon mineralization and microbial community structure. *PLOS ONE*, *14*(1), e0211163. https://doi.org/10.1371/journal.pone.0211163

Hao, F., Liu, Z., Zhen, Z., & Wang, Z. (2024). Impact of different types of nitrogen and phosphorus compound fertilizers on maize yield and drip emitter clogging using secondary sewage effluent. *Frontiers in Environmental Science*, *12*. https://doi.org/10.3389/fenvs.2024.1502902

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)* (Issue 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)

Ibrahim, M. M., Guo, L., Wu, F., Liu, D., Zhang, H., Zou, S., Xing, S., & Mao, Y. (2022). Field-applied biochar-based MgO and sepiolite composites possess CO2 capture potential and alter organic C mineralization and C-cycling bacterial structure in fertilized soils. *Science of The Total Environment*, *813*, 152495. https://doi.org/10.1016/j.scitotenv.2021.152495

Inguscio, A. (2022). The EU Perspective from Setbacks to Success: Tackling Climate Change from Copenhagen to the Green Deal and the Next-Generation EU. In S. Valaguzza & M. A. Hughes (Eds.), *Interdisciplinary Approaches to Climate Change for Sustainable Growth* (pp. 127–139). Springer International Publishing. https://doi.org/10.1007/978-3-030-87564-0_8

Izydorczyk, G., Sienkiewicz-Cholewa, U., Baśladyńska, S., Kocek, D., Mironiuk, M., & Chojnacka, K. (2020). New environmentally friendly bio-based micronutrient fertilizer by biosorption: From laboratory studies to the field. *Science of The Total Environment*, *710*, 136061. https://doi.org/10.1016/j.scitotenv.2019.136061

Jacquet, F., Jeuffroy, M.-H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., & Huyghe, C. (2022). Pesticide-free agriculture as a new paradigm for research. *Agronomy for Sustainable Development*, *42*(1), 8. https://doi.org/10.1007/s13593-021-00742-8

Jama-Rodzeńska, A., Białowiec, A., Koziel, J. A., & Sowiński, J. (2021). Waste to phosphorus: A transdisciplinary solution to P recovery from wastewater based on the TRIZ approach. In *Journal of Environmental Management* (Vol. 287). Academic Press. https://doi.org/10.1016/j.jenvman.2021.112235

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

Jensen, L. S., Oelofse, M., Hoeve, M. ten, & Bruun, S. (2020). Environmental Impact Assessment on the Production and Use of Biobased Fertilizers. In E. Meers, Gerard Velthof, E. Michels, & R. Rietra (Eds.), *Biorefinery ofInorganics: Recovering Mineral Nutrients from Biomass and Organic Waste*. John Wiley & Sons Ltd.

Jian, J., Du, X., & Stewart, R. D. (2020). A database for global soil health assessment. *Scientific Data*, *7*(1), 16. https://doi.org/10.1038/s41597-020-0356-3

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, Issue 1). MDPI. https://doi.org/10.3390/en15010385

Kassai, P., & Tóth, G. (2020). Agricultural soil phosphorus in Hungary: High resolution mapping and assessment of socioeconomic and pedological factors of spatiotemporal variability. *Sustainability (Switzerland)*, *12*(13). https://doi.org/10.3390/su12135311

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

Kratz, S., & Hermann, L. (2020). *Report on the legal framework governing the use of nutrient rich side streams (NRSS) as biobased fertilisers (BBFs), EU legislation*. https://doi.org/10.5073/berjki.2020.208.000

Kurniawati, A., Melati, M., Aziz, S. A., & Purwono, D. (2017). Pengurangan Dosis Pupuk pada Produksi Sawi Hijau Organik dengan Pergiliran Tanaman Jagung dan Kedelai. *Jurnal Agronomi Indonesia (Indonesian Journal of Agronomy)*, *45*(2), 188. https://doi.org/10.24831/jai.v45i2.12961

Kurniawati, A., Windriyati, R. D. H., Wulansari, N. K., Toth, G., & Toth, Z. (2021). Alternatives for Circular Bioeconomy in Organic Farming under Excessive Nutrients (Goat manure and Arbuscular Mycorrhizal Fungi): A Case Study in Indonesia. *Sustainability*, *13*(22), 12333. https://doi.org/10.3390/su132212333

Kyakuwaire, Olupot, Amoding, Nkedi-Kizza, & Basamba. (2019). How Safe is Chicken Litter for Land Application as an Organic Fertilizer? A Review. *International Journal of Environmental Research and Public Health*, *16*(19), 3521. https://doi.org/10.3390/ijerph16193521

Lähteenmäki-Uutela, A., Rahikainen, M., Camarena-Gómez, M. T., Piiparinen, J., Spilling, K., & Yang, B. (2021). European Union legislation on macroalgae products. *Aquaculture International*, *29*(2), 487–509. https://doi.org/10.1007/s10499-020-00633-x

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, *1*(10), 544–553. https://doi.org/10.1038/s43017-020-0080-8

Linares, J., Scholberg, J., Boote, K., Chase, C. A., Ferguson, J. J., & Mcsorley, R. (2008). Use of the Cover Crop Weed Index to Evaluate Weed Suppression by Cover Crops in Organic Citrus Orchards. *HortScience*, *43*(1), 27. https://doi.org/10.21273/HORTSCI.43.1.27

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

Liu, X., Selonen, V., Steffen, K., Surakka, M., Rantalainen, A.-L., Romantschuk, M., & Sinkkonen, A. (2019). Meat and bone meal as a novel biostimulation agent in hydrocarbon contaminated soils. *Chemosphere*, *225*, 574–578. https://doi.org/10.1016/j.chemosphere.2019.03.053

Lourenzi, C. R., Ceretta, C. A., Ciancio, N. H. R., Tiecher, T. L., da Silva, L. O. S., De Conti, L., Girotto, E., Ferreira, P. A. A., Vidal, R. F., Scopel, G., Marchezan, C., & Brunetto, G. (2021). Forms of nitrogen and phosphorus transfer by runoff in soil under no-tillage with successive organic waste and mineral fertilizers applications. *Agricultural Water Management*, *248*, 106779. https://doi.org/10.1016/j.agwat.2021.106779

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

Luyckx, L., Sousa Correia, D. S., & Van Caneghem, J. (2021). Linking Phosphorus Extraction from Different Types of Biomass Incineration Ash to Ash Mineralogy, Ash Composition and Chemical Characteristics of Various Types of Extraction Liquids. *Waste and Biomass Valorization*, *12*(9), 5235–5248. https://doi.org/10.1007/s12649-021-01368-3

Ma, Y., Yin, Y., & Liu, Y. (2017). A holistic approach for food waste management towards zero-solid disposal and energy/resource recovery. *Bioresource Technology*, *228*, 56–61. https://doi.org/10.1016/j.biortech.2016.12.090

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

Marini, M., Caro, D., & Thomsen, M. (2020). The new fertilizer regulation: A starting point for cadmium control in European arable soils? *Science of The Total Environment*, *745*, 140876. https://doi.org/10.1016/J.SCITOTENV.2020.140876

Masud, M. M., Baquy, M. A.-A., Akhter, S., Sen, R., Barman, A., & Khatun, M. R. (2020). Liming effects of poultry litter derived biochar on soil acidity amelioration and maize growth. *Ecotoxicology and Environmental Safety*, *202*, 110865. https://doi.org/10.1016/j.ecoenv.2020.110865

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

Mekki, A., Aloui, F., & Sayadi, S. (2019). Influence of biowaste compost amendment on soil organic carbon storage under arid climate. *Journal of the Air & Waste Management Association*, *69*(7), 867–877. https://doi.org/10.1080/10962247.2017.1374311

Menšík, L., Hlisnikovský, L., Pospíšilová, L., & Kunzová, E. (2018). The effect of application of organic manures and mineral fertilizers on the state of soil organic matter and nutrients in the long-term field experiment. *Journal of Soils and Sediments*, *18*(8), 2813–2822. https://doi.org/10.1007/s11368-018-1933-3

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

Monlau, F., Suarez-Alvarez, S., Lallement, A., Vaca-Medina, G., Giacinti, G., Munarriz, M., Urreta, I., Raynaud, C., Ferrer, C., & Castañón, S. (2021). A cascade biorefinery for the valorization of microalgal biomass: biodiesel, biogas, fertilizers and high valuable compounds. *Algal Research*, *59*. https://doi.org/10.1016/j.algal.2021.102433

Mortola, N., Romaniuk, R., Cosentino, V., Eiza, M., Carfagno, P., Rizzo, P., Bres, P., Riera, N., Roba, M., Butti, M., Sainz, D., & Brutti, L. (2019). Potential Use of a Poultry Manure Digestate as a Biofertiliser: Evaluation of Soil Properties and Lactuca sativa Growth. *Pedosphere*, *29*(1), 60–69. https://doi.org/10.1016/S1002-0160(18)60057-8

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

Okolie, J. A., Epelle, E. I., Tabat, M. E., Orivri, U., Amenaghawon, A. N., Okoye, P. U., & Gunes, B. (2022). Waste biomass valorization for the production of biofuels and value-added products: A comprehensive review of thermochemical, biological and integrated processes. In *Process Safety and Environmental Protection* (Vol. 159, pp. 323–344). Institution of Chemical Engineers. https://doi.org/10.1016/j.psep.2021.12.049

Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. (2021). Chemical Fertilizers and Their Impact on Soil Health. In G. H. Dar, R. A. Bhat, M. A. Mehmood, & K. R. Hakeem (Eds.), *Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs* (pp. 1–20). Springer International Publishing. https://doi.org/10.1007/978-3-030-61010-4_1

Panuccio, M. R., Romeo, F., Mallamaci, C., & Muscolo, A. (2021). Digestate Application on Two Different Soils: Agricultural Benefit and Risk. *Waste and Biomass Valorization*, *12*(8), 4341–4353. https://doi.org/10.1007/s12649-020-01318-5

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

Ramawat, N., & Bhardwaj, V. (2022). *Biostimulants: Exploring Sources and Applications* (N. Ramawat & V. Bhardwaj, Eds.). Springer Nature Singapore. https://doi.org/10.1007/978-981-16-7080-0

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

Roper, W. R., Osmond, D. L., Heitman, J. L., Wagger, M. G., & Reberg-Horton, S. C. (2017). Soil Health Indicators Do Not Differentiate among Agronomic Management Systems in North Carolina Soils. *Soil Science Society of America Journal*, *81*(4), 828–843. https://doi.org/10.2136/sssaj2016.12.0400

Roy, E. D. (2017). Phosphorus recovery and recycling with ecological engineering: A review. In *Ecological Engineering* (Vol. 98, pp. 213–227). Elsevier B.V. https://doi.org/10.1016/j.ecoleng.2016.10.076

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

Sarvajayakesavalu, S., Lu, Y., Withers, P. J. A., Pavinato, P. S., Pan, G., & Chareonsudjai, P. (2018). Phosphorus recovery: a need for an integrated approach. In *Ecosystem Health and Sustainability* (Vol. 4, Issue 2, pp. 48–57). Taylor and Francis Ltd. https://doi.org/10.1080/20964129.2018.1460122

Sena, M., Seib, M., Noguera, D. R., & Hicks, A. (2021). Environmental impacts of phosphorus recovery through struvite precipitation in wastewater treatment. *Journal of Cleaner Production*, *280*, 124222. https://doi.org/10.1016/j.jclepro.2020.124222

Sigurnjak, I., Brienza, C., Snauwaert, E., De Dobbelaere, A., De Mey, J., Vaneeckhaute, C., Michels, E., Schoumans, O., Adani, F., & Meers, E. (2019). Production and performance of bio-based mineral fertilizers from agricultural waste using ammonia (stripping-)scrubbing technology. *Waste Management*, *89*, 265–274. https://doi.org/10.1016/j.wasman.2019.03.043

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

Silvasy, T., Ahmad, A. A., Wang, K.-H., & Radovich, T. J. K. (2021). Rate and Timing of Meat and Bone Meal Applications Influence Growth, Yield, and Soil Water Nitrate Concentrations in Sweet Corn Production. *Agronomy*, *11*(10), 1945. https://doi.org/10.3390/agronomy11101945

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

Solaiman, Z. M., Shafi, M. I., Beamont, E., & Anawar, H. M. (2020). Poultry Litter Biochar Increases Mycorrhizal Colonisation, Soil Fertility and Cucumber Yield in a Fertigation System on Sandy Soil. *Agriculture*, *10*(10), 480. https://doi.org/10.3390/agriculture10100480

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

Stürmer, B., Pfundtner, E., Kirchmeyr, F., & Uschnig, S. (2020). Legal requirements for digestate as fertilizer in Austria and the European Union compared to actual technical parameters. *Journal of Environmental Management*, *253*, 109756. https://doi.org/10.1016/j.jenvman.2019.109756

The European Commission. (2014). *Communication from the Commission - Towards a circular economy: A zero waste programme for Europe (COM no. 398, 2014)*.

The European Commission. (2015). *Communication from the Commission. Closing the loop - An EU action plan for the Circular Economy (COM no. 614, 2015)*.

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 Commission. (2020a). *A Farm to Fork Strategy: for a fair, healthy and environmentally-friendly food system (COM no. 381 2020 final)*.

The European Commission. (2020b). *Communication from the Commission. Circular Economy Action Plan for a cleaner and more competitive Europe (COM no. 98, 2020)*.

The European Commission. (2021). *Communication from The Commission To The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions Pathway to a Healthy Planet for All EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil' COM/2021/400 final*.

The European Council. (1986). *Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31986L0278

The European Council. (1992). *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31992L0043

The European Council. (2017). *European Commission, 2017. Commision Implementing Regulation (EU) 2017/1242 of 10 July 2017 amending Implementing Regulation (EU) No 809/2014 laying down rules for the application of Regulation (EU) No 1306/2013 of the European Parliament and of the Coun*. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32017R1242&from=HU

The European Council. (2019). *New Green Deal, Communication from the Commission to the European Parliament, the European Council, the Council, The European Economic and Social Committee and the Committee Of The Regions The European Green Deal Com/2019/640 Final*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

The European Council. (2021a). *EU Adaptation Strategy*. https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en

The European Council. (2021b). *European Climate Law, Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999*. http://data.europa.eu/eli/reg/2021/1119/oj

The European Parliement and The Council. (2010). *Directive 2009/147/EC of The European Parliement and of The Council of 30 November 2009 on the conservation of wild birds (codified version)*.

The European Union. (2006). *1907/2006: Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals/ REACH*. https://echa.europa.eu/regulations/reach/legislation

The European Union. (2012). *TFEU: Consolidated version of the Treaty on the Functioning of the European Union Article 47 of the Charter of Fundamental Rights of the European Union*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A12012E%2FTXT

The European Union. (2016). *Circular economy: New Regulation to boost the use of organic and waste-based fertilisers*. https://ec.europa.eu/commission/presscorner/detail/de/MEMO_16_826%0A

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

The European Union. (2021a). *Proposal For A Regulation of The European Parliament and of The Council on the sustainable use of plant protection products and amending Regulation (EU) 2021/2115*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A305%3AFIN

The European Union. (2021b). *Sustainable development in the European Union*. Routledge. https://doi.org/10.2785/195273

The European Union. (2022). *Opinion of the European Economic and Social Committee on the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on EU Soil Strategy for 2030 — Reaping the*. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021AE5627

The fertilizer institute. (2016). *State of The Fertilizer Industry*. https://www.tfi.org/resource-library/industry-topics/sustainability-resources/?mg_page=1

The Your Europe. (2022). *Conformity assessment*. https://europa.eu/youreurope/business/product-requirements/compliance/conformity-assessment/index_en.htm

Tonini, D., Saveyn, H. G. M., & Huygens, D. (2019). Environmental and health co-benefits for advanced phosphorus recovery. *Nature Sustainability*, *2*(11), 1051–1061. https://doi.org/10.1038/s41893-019-0416-x

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

Urra, Alkorta, & Garbisu. (2019). Potential Benefits and Risks for Soil Health Derived From the Use of Organic Amendments in Agriculture. *Agronomy*, *9*(9), 542. https://doi.org/10.3390/agronomy9090542

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

Wang, J.-Y., Stabnikova, O., Tay, T.-L., Ivanov, V., & Tay, J.-H. (2004). Biotechnology of intensive aerobic conversion of sewage sludge and food waste into fertilizer. *Water Science and Technology*, *49*(10), 147–154. http://www.nea.gov.sg

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

Wessells, K. R., & Brown, K. H. (2012). Estimating the Global Prevalence of Zinc Deficiency: Results Based on Zinc Availability in National Food Supplies and the Prevalence of Stunting. *PLoS ONE*, *7*(11), e50568. https://doi.org/10.1371/journal.pone.0050568

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

Xu, P., Liu, Y., Zhu, J., Shi, L., Fu, Q., Chen, J., Hu, H., & Huang, Q. (2020). Influence mechanisms of long-term fertilizations on the mineralization of organic matter in Ultisol. *Soil and Tillage Research*, *201*, 104594. https://doi.org/10.1016/j.still.2020.104594

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

Zhou, X., Wang, J., Lu, C., Liao, Q., Gudda, F. O., & Ling, W. (2020). Antibiotics in animal manure and manure-based fertilizers: Occurrence and ecological risk assessment. *Chemosphere*, *255*. https://doi.org/10.1016/j.chemosphere.2020.127006

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, Issue 26, pp. 15977–15988). Royal Society of Chemistry. https://doi.org/10.1039/d1ra00355k

8.2. Summary of statistical output (ANOVA tables) for all data presented

Table 1. Analysis of variance for the effect of BBF application on plant height of maize in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	3360.41	3	1120.14	3.71	
Treatment	3048.94	12	254.078	0.84	0.61[ns]
Residual	10855.07	36	301.53		
Total	17264.43	51	338.52		

*significant at 5% probability level, **significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 2. Analysis of variance for the effect of BBF application on leaf number of maize in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	3.60	3	1.19	1.35	
Treatment	4.79	12	0.39	0.45	0.93[ns]
Residual	32.02	36	0.88		
Total	40.41	51	0.79		

*significant at 5% probability level, **significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 3. Analysis of variance for the effect of BBF application on stem diameter of maize in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.14	3	0.05	2.66	
Treatment	0.15	12	0.01	0.67	0.76[ns]
Residual	0.65	36	0.02		
Total	0.94	51	0.02		

*significant at 5% probability level, **significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 4. Analysis of variance for the effect of BBF application on total leaf area per plant of maize in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.23	3	0.08	7.10	
Treatment	0.10	12	0.01	0.77	0.67[ns]
Residual	0.39	36	0.01		
Total	0.72	51	0.01		

*significant at 5% probability level, **significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 5. Analysis of variance for the effect of BBF application on soil phosphorus content (Olsen P) in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	357.14	3	119.05	8.03	
Treatment	107.93	12	8.99	0.61	0.82[ns]
Residual	533.43	36	14.82		
Total	998.50	51	19.58		

*significant at 5% probability level, **significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 6. Analysis of variance for the effects of BBF application on above-ground biomass (fresh weight) of maize in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	21564121.13	3	7188040.38	6.48	
Treatment	10030047.27	12	835837.27	0.75	0.69^{ns}
Residual	39959330.12	36	1109981.39		
Total	71553498.52	51	1403009.77		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 7. Analysis of variance for the effects of BBF application on above-ground biomass (dry weight) of maize in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	16564638.46	3	5521546.15	6.46	
Treatment	7863369.23	12	655280.77	0.77	0.68^{ns}
Residual	30754661.54	36	854296.15		
Total	55182669.23	51	1082013.12		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 8. Analysis of variance for the effect of BBF application on P uptake of maize biomass in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	6.34	3	2.11	0.30	
Treatment	51.49	12	4.29	0.60	0.82^{ns}
Residual	255.56	36	7.10		
Total	313.39	51	6.14		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 9. Analysis of variance for the effect of BBF application on N uptake of maize biomass in year one

EFFECT	SS	DF	MS	F	ProbF
Blocks	100.84	3	33.61	0.14	
Treatment	3671.74	12	305.98	1.27	0.28^{ns}
Residual	8662.56	36	240.63		
Total	12435.14	51	243.83		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 10. Analysis of variance for the effect of BBF application on the fresh grain weight of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	6362147.23	3	2120715.74	18.80	
Treatment	1462631.08	12	121885.92	1.08	0.40^{ns}
Residual	4060290.77	36	112785.85		
Total	11885069.08	51	233040.57		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 11. Analysis of variance for the residual effect of BBF application on the fresh grain weight of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	8138452.54	3	2712817.51	20.79	
Treatment	2139253.81	12	178271.15	1.37	0.23^{ns}
Residual	4696600.96	36	130461.14		
Total	14974307.31	51	293613.87		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 12. Analysis of variance for the effect of BBF application on the fresh biomass of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	2613079.38	3	871026.46	2.40	
Treatment	7842855.74	12	653571.31	1.80	0.09^{ns}
Residual	13084934.88	36	363470.41		
Total	23540870.00	51	461585.69		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 13. Analysis of variance for the residual effect of BBF application on the fresh biomass of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	2860360.77	3	953453.59	2.74	
Treatment	5471215.24	12	455934.60	1.31	0.26^{ns}
Residual	12539872.68	36	348329.80		
Total	20871448.70	51	409244.09		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 14. Analysis of variance for the effect of BBF application on the grain yield of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	5284507.52	3	1761502.51	19.00	
Treatment	1080218.71	12	90018.23	0.97	0.49^{ns}
Residual	3336725.41	36	92686.82		
Total	9701451.64	51	190224.54		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 15. Analysis of variance for the residual effect of BBF application on the grain yield of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	6834376.92	3	2278125.64	21.32	
Treatment	1555995.73	12	129666.31	1.21	0.3^{ns}
Residual	3847129.35	36	106864.70		
Total	12237502.01	51	239951.02		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 16. Analysis of variance for the effect of BBF application on the dry biomass of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	2232676.68	3	744225.56	2.42	
Treatment	6577264.92	12	548105.41	1.78	0.09[ns]
Residual	11074820.47	36	307633.90		
Total	19884762.08	51	389897.30		

[*]significant at 5% probability level, [**]significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 17. Analysis of variance for the residual effect of BBF application on the dry biomass of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	2444984.39	3	814994.80	2.76	
Treatment	4642037.40	12	386836.45	1.31	0.26[ns]
Residual	10638504.87	36	295514.02		
Total	17725526.66	51	347559.35		

[*]significant at 5% probability level, [**]significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 18. Analysis of variance for the effect of BBF application on the grain P concentration of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.004	3	0.001	1.045	
Treatment	0.040	12	0.003	2.409	0.021[*]
Residual	0.049	36	0.001		
Total	0.093	51	0.002		

[*]significant at 5% probability level, [**]significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 19. Analysis of variance for the residual effect of BBF application on the grain P concentration of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.006	3	0.002	1.094	
Treatment	0.026	12	0.002	1.117	0.377[ns]
Residual	0.070	36	0.002		
Total	0.103	51	0.002		

[*]significant at 5% probability level, [**]significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 20. Analysis of variance for the effect of BBF application on the biomass P concentration of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.004	3	0.001	0.927	
treatment	0.042	12	0.004	2.269	0.029[*]
Residual	0.056	36	0.002		
Total	0.102	51	0.002		

[*]significant at 5% probability level, [**]significant at 1% probability level, [ns] non-significant at 5% probability level.

Table 21. Analysis of variance for the residual effect of BBF application on the biomass P concentration of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.11	3	0.04	1.35	
Treatment	0.42	12	0.04	1.30	0.26^{ns}
Residual	0.97	36	0.03		
Total	1.50	51	0.03		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 22. Analysis of variance for the effect of BBF application on the grain N concentration of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	1.28	3	0.43	17.74	
Treatment	0.29	12	0.02	1.02	0.46^{ns}
Residual	0.87	36	0.02		
Total	2.44	51	0.05		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 23. Analysis of variance for the residual effect of BBF application on the grain N concentration of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.56	3	0.19	9.70	
Treatment	0.51	12	0.04	2.21	0.03^{*}
Residual	0.69	36	0.02		
Total	1.76	51	0.03		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 24. Analysis of variance for the effect of BBF application on the biomass N concentration of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.76	3	0.25	4.59	
Treatment	0.96	12	0.08	1.44	0.19^{ns}
Residual	1.99	36	0.06		
Total	3.71	51	0.07		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 25. Analysis of variance for the residual effect of BBF application on the biomass N concentration of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.88	3	0.29	2.92	
Treatment	1.67	12	0.14	1.38	0.22^{ns}
Residual	3.64	36	0.10		
Total	6.19	51	0.12		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 26. Analysis of variance for the effect of BBF application on the soil P content of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	34.53	3.00	11.51	1.75	
treatment	62.99	12.00	5.25	0.80	0.65^{ns}
Residual	236.17	36.00	6.56		
Total	333.69	51.00	6.54		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 27. Analysis of variance for the residual effect of BBF application on the soil P content of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	8.91	3	2.97	2.15	
treatment	16.16	12	1.35	0.98	0.49^{ns}
Residual	49.68	36	1.38		
Total	74.75	51	1.47		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 28. Analysis of variance for the effect of BBF application on the total P uptake of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	0.98	3	0.33	3.74	
treatment	2.61	12	0.22	2.50	0.02^{*}
Residual	3.13	36	0.09		
Total	6.72	51	0.13		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 29. Analysis of variance for the residual effect of BBF application on the total P uptake of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	5.41	3	1.80	2.40	
treatment	8.53	12	0.71	0.95	0.51^{ns}
Residual	27.04	36	0.75		
Total	40.97	51	0.80		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 30. Analysis of variance for the effect of BBF application on the total N uptake of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	2064.24	3	688.08	2.73	
treatment	2738.24	12	228.19	0.91	0.55^{ns}
Residual	9072.05	36	252.00		
Total	13874.53	51	272.05		

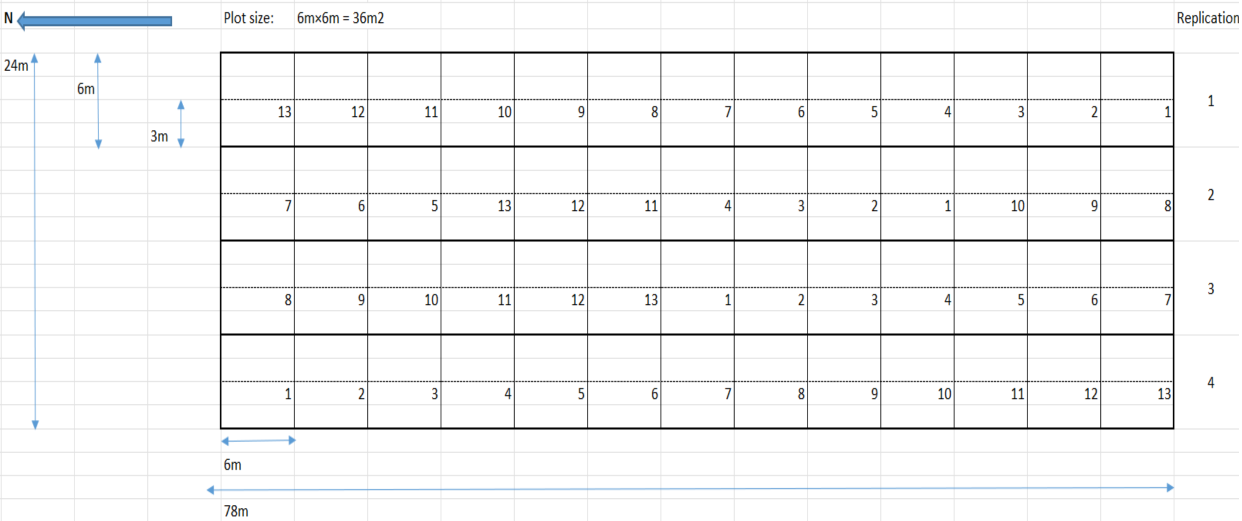
*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

Table 31. Analysis of variance for the residual effect of BBF application on the total N uptake of winter wheat in the second year

EFFECT	SS	DF	MS	F	ProbF
Blocks	10262.40	3	3420.80	12.28	
treatment	2236.77	12	186.40	0.67	0.77^{ns}
Residual	10032.44	36	278.68		
Total	22531.61	51	441.80		

*significant at 5% probability level, **significant at 1% probability level, ^{ns} non-significant at 5% probability level.

8.3. Layout of the experimental plots during the two study years



The black lines illustrate the configuration used in the first year (6 m × 6 m). In the second year, shown by dashed lines, the field was divided into two parts, resulting in smaller plots (6 m × 3 m).