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REVIEW

Opportunities and challenges of bio-based fertilizers utilization for improving soil health

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Abstract Bio-based fertilizers (BBFs) have been promoted as a solution to help manage bio-waste problems and improve soil health conditions. Their potential is to replace mineral fertilizers due to non-renewable energy dependency and the accumulation that threatens environmental issues. Currently, laboratory and field-based literature have been growing since European Union (EU) looks BBFs as the future of agriculture bio-based products. Nevertheless, it is worth to summarizing the results on a regular basis. The added value of this work is to study the opportunities of bio-based fertilizer utilization to sustain plant productivity and investigate the challenges to water footprints and human health. This study found that contamination of heavy metals and pathogens is the main problems of BBFs implementation which need more attention to develop the technology process including the environmental risk assessments. Furthermore, compared to mineral fertilizers, BBFs have obstacles to getting social acceptance due to the challenges of transportation and production cost, the concentration of nutrients, matching crops, and policy framework. To sum up, BBF is a long-run scheme that should be started to tackle global issues since the potency as energy alternative sources to support the circular economy paradigm.

Keywords Soil conservation · Sustainable agriculture · Human health · Circular bioeconomy · Agroecology

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Abbreviations

BBFs	Bio-based fertilizers
FPR	Fertilizing products regulation
CMC	Component material category
PFC	Product function category
P	Phosphorus
N	Nitrogen
K	Kalium
EU	European Union
STRUBIAS	(STRUvite/recovered phosphate salts, BIochars/pyrolysis materials, ASh-based products)
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
GHG	Greenhouse gas
TRLs	Technology readiness levels
LCC	Life cycle cost
S-LCA	Social life cycle assessment

Introduction

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

Agriculture sector has a crucial role in achieving food security. Regardless the energy alternative sources, there is another challenge related to soil health. The intensive agricultural operations and unsustainable land-use management practices have caused the decline in soil health and crop yield (Jian et al., 2020). Soil health covers soil fertility, soil quality, and soil security due to the broad function that sustains the living system. Soil quality is related to soil function that includes metrics of soil fertility and a fundamental natural resources like water and air (Laishram et al., 2012), whereas soil security is an integrated approaches to land management, while balancing ecosystem services, environmental, social, cultural, and economic imperatives (Bennett et al., 2019) based on soil quality. Therefore, the determination for soil health management decisions and goals is needed to optimize efforts in improving soil health. Linked environmental challenge for future food sector will be as a main consideration.

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 mineral 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. 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 mineral fertilizers, disrupting the stability of fertilizer supply.

Furthermore, Menšík et al. (2018) reported that long-term application of mineral 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 waters and leach to groundwater which can pollute the environments. The increase rate of N fertilizer during the early days after fertilizer application significantly enhanced the N loss in paddy field (Cui et al., 2020). These issues drag the consideration for another alternative solution: bio-based fertilizers (BBFs).

The potential of bio-based fertilizers is clearly needed to be continued for maintaining soil health because of nutrients mineralization opportunities in the agricultural system. Chicken manure-based fertilizer possessed large fractions of the total N, P, and K available to the crops (Mažeika et al., 2021). On the other hand, the availability of the raw materials for BBFs production is also abundant. In 2017, the EU-28 (28 EU Member States) generated 86 million tonnes of biowaste or 34% of municipal solid waste (European Environment Agency, 2020) in which unmanaged waste can cause serious environmental and health problems. In developing countries, the situation is even worst; the main food waste streams come from food market activities/areas, where it is usual to have a high production and a non-efficient waste management (Jara-Samaniego et al., 2017).

Several studies have been done to process waste by-products into a 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 aligns with the farmer's preference of expecting the nutrient content in BBFs to be the same as in the mineral 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. Moreover, related to resource availability in BBFs production, a cross-sectorial vision is required to bridge the gap between agricultural residues science and business opportunities in order 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 mineral fertilizer by the addition of BBFs to substitute plant nutrients (Borges et al., 2019; Mažeika et al., 2021). Moreover, N losses (including NH_3, N_2O emissions, and N leaching) can be reduced by 50% substitution of manure for chemical N fertilizers (S. Guo et al., 2020). Even, there was no significant differences in respect to product characterization and fertilizer performance of BBFs compared to mineral fertilizer (Cheong et al., 2020; Dubis et al., 2020; Grillo et al., 2021; Sigurnjak et al., 2019). Nevertheless, the question remains on how big is the impacts on soil health? What parameters of soil health that are affected by BBFs? An adequate assessment approach which provides proper insight and guidance on the seasonality, regional aspects, and complexity of — among others — agricultural residue management chains is needed (Gontard et al., 2018) to check the effects of BBFs not only on crop production but also on soil health in general.

To address this gap, we collected the studies about the use of BBFs on agricultural production and its effects on soil health: the opportunities and challenges. The recent publications could be used for future research perspective in the long-term implementation of BBFs that can meet specific criteria for new eco-friendly fertilizers, including to supply nutrients for plants and to continue capacity of soil for living ecosystem (soil health). Furthermore, the information is expected to asses and guide management practices in terms of BBFs utilization.

The bio-based fertilizers and conditioners

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 mineral fertilizers (Jensen et al., 2020).

To be seen fairly, in terms of actual nutrient content, mineral 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 product sometimes generates air pollution because they still leave the odor after processing, especially 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.

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.

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 $\geq$ 15% and $\geq$5% carbon (C) organic, respectively), organo-mineral (solid and liquid organo-mineral fertilizer were $\geq$ 7.5% and $\geq$3% C organic, respectively), and mineral type fertilizers (straight and compound solid inorganic macronutrient fertilizer) to be mentioned as fertilizer.

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.

Table 1 Analysis 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	Crystallization	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 content 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 (classified as iso-humic soil with dominantly coarse texture) 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 mineral fertilizers suggesting that they can be an effective substitute for mineral fertilizers in intensive cropping systems, but long-term experiment is needed to evaluate solid digestate fraction sustainability

Source: Authors elaboration, 2023

Soil health indicators affected by bio-based fertilizers use

According to Lehmann et al. (2020), "Soil health is the continued capacity of soil to function as a vital living ecosystem to support the sustainability of plants, animals and humans, and connect agricultural and soil science to policy, stakeholder needs, and sustainable supply-chain management." The concept of soil health has emerged from soil quality to "One Health" concept in which the health of humans, animals, and environments are all connected. It can be seen also in the Fig. 1 showing five big cluster of soil health indicators: soil quality that can support plant production (red nodes), environmental exposure related to human health (green nodes), water quality (blue nodes), microbial community (purple nodes), and general indicators (yellow nodes).

The figure was obtained by VOSviewer tool based on metadata search results on Scopus database. Nine-hundred twenty-eight articles were found from 2019 to 2022 with the keyword "soil health indicator" limited to subject area of environmental, agricultural, and biological sciences. Metadata saved in .csv (comma separated values) format was visualized using VOSviewer software.

Stewart et al. (2018) grouped soil health inidicators into six categories: physical properties (e.g.,

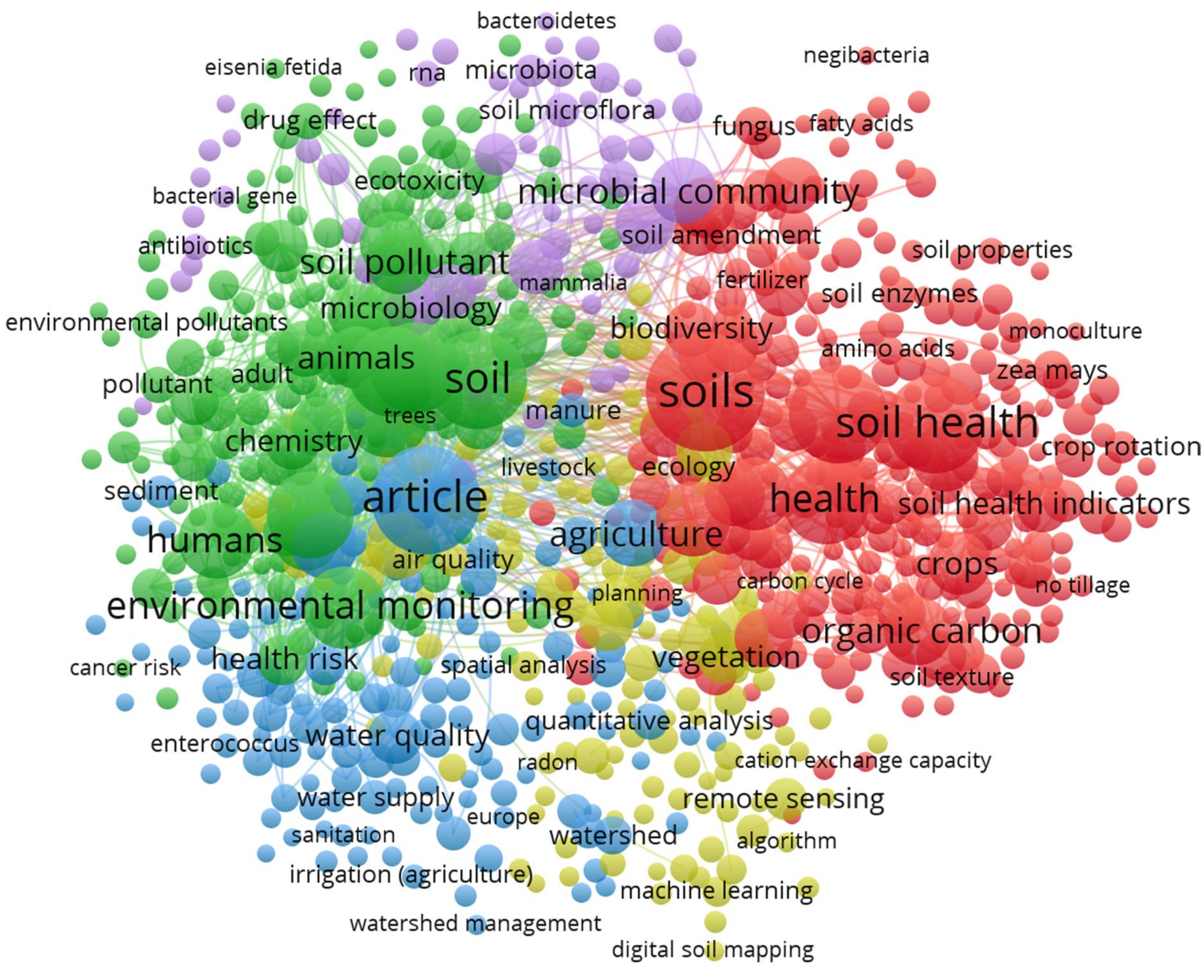

Fig. 1 Soil health indicator network visualization. Legend: Color, represents big cluster of disciplines in the research field; nodes, represents keywords (the size of node represents the keywords frequency); links, represent relations between keywords (keywords mentioned together in published articles); colors, represent the temporal orders of appearance of keywords; link thickness, represents the words strength. Source: Researcher, derived from VOSviewer

aggregate stability, penetration resistance, available water capacity), chemical characteristics (pH, P, K, micronutrients, organic matter content), biological indicators (soil proteins, soil respiration, soil pathogens), environmental states and fluxes (erosion, runoff), agronomic responses (crop yield and crop biomass), and general indicators (soil quality indicators and ecosystem services). These indicators can be affected by agricultural management practices, including fertilization (Table 2).

Each soil health indicator affected by fertilization is connected because the addition or depletion of inputs in the soil influences the soil temperature and water-holding capacity as well as functioning as reservoir of the microorganism. For instance, in Table 2, even though Mažeika et al. (2021) did not observe parameters related to physical and biological properties after the application of chicken manure, the nutrient availability in the soil was expected by the activity of phosphate solubilizing bacteria and K-dissolving bacteria. Directly, the presence of the microorganisms was also influenced by the adequate living environment and energy sources. It is well known that physical and chemical properties influence microbial activities and are related to soil fertility.

For chemical properties, BBFs may provide low nutrient concentration compared to mineral fertilizers in the equal quantity. However, the use of BBFs such as MBM has the potential to replace mineral N and P fertilizers, although the additional potassium fertilizer was needed due to low concentration of K (0.3–0.8% K) (Silvasy et al., 2021; Szymczyk & Stępień, 2018). Improvement or additional nutrient sources in BBFs production can be considered in some raw materials to comply the nutrients needed by plants.

Furthermore, the other indicators are geared towards nonagricultural soil services, such as water quality, human health, and climate change. In this ecosystem services, BBFs are taking the challenge as soil improver or polluter. According to Scopetani et al. (2022), compost can represent a source of plastic contamination to the agricultural fields. Hence, this is a homework of BBFs application due to the contaminants requiring sanitation process and degradation strategies on its implementation.

As soil improver, BBFs improve soil texture due to the increase of organic matter as food sources for soil microbes, such as bacteria and fungi. Arbuscular mycorrhizal fungi (AMF) was higher under manure additions compared to inorganic fertilizer (Ozlu et al., 2019). A similar result was found by Pokhrel et al. (2021) that showed the increase of easily extractable glomalin-related soil protein produced by AMF with respect to poultry litter application. Soil microorganisms are the main players in soil biochemical processes which are closely related to soil organic carbon mineralization processes and nutrient cycling.

A novel BBF produced should meet the criteria to be approved for sustainable agriculture by

Table 2 The effect of BBFs on soil health indicators

Author	BBFs	Type of indicator			
		Physical properties	Chemical properties	Biological properties	Ecosystem services
Cheong et al. (2020)	Food waste anaerobic digestate (FWAD)	• Improve soil texture	• Rich organic matter • Provide nutrients	• High bacterial communities	-
Mažeika et al. (2021)	Chicken manure	-	• Maintain nutrient content	• Microbial activity was expected	-
Ibrahim et al. (2022)	Modified biochars	-	• Increase mineralization of organic C • Improve soil pH	• Increase diversity of soil C-cycling bacteria	• Improve the capture of CO_2
Shen et al. (2020)	Organic fertilizer	-	• Alter pH and EC values	-	• Minimize bioavailable of Cd and As
Laurent et al. (2020)	Organic fertilizer	-	• Alter soil pH and dissolved organic matter	-	• Decrease Cu and Zn contaminant

-, not studied; *P*, ecosystem services including water quality, human health, and climate control considering not only the nutrient contents but also the environmental exposures and its impact on soil properties. A high nutrient contents and giving high potential yield of plants are not enough to be used as a future prospective fertilizer. Hence, soil health indicators are point to be noted in BBF production. This standardization can set the protocols based on indicators which allow the community to better strategize and prioritize efforts to improve soil health across diverse systems.

The effects of bio-based material on soil health and soil ecosystem services

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 agicultural 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 mineral 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 mineral 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 (Guo et al., 2019). Based on the research, long-term experiments showed the potential of BBF utilization sole or mixed with mineral fertilizer.

Support integrated farming

The concept of BBF utilization can be also used as the implementation of integrated farming because its use is not only to replace mineral fertilizer in the future but also to close the loop within cropland farming at the regional level under different pedoclimate conditions. The integration between animal farming, crop production, and industrial waste could be implemented for optimization of energy resources. Thanh Hai et al. (2020) showed that an integrated farming system improves agricultural productivity, minimizes the amount of waste, and increases the family income up to 41.55% for the community in rural areas.

Research on waste management supported integrated farming showing that the collection of biowastes treated locally in new biogas plant had an advantage over collected biowastes transported and treated in existing biogas plant (Airi, 2019). This condition may reduce cost on crop production due to the purchase of external input (mineral fertilizer) due to the use of local fertilizer from the biogas plant, and transportation cost of fertilizer also can be disregarded. On the other hand, waste problem can be managed locally via upcycling to produce organic fertilizer which improves soil fertility and increases nutrient use efficiency. Chojnacka et al. (2020) also agreed that it is necessary to construct small wastes solubilization or fertilizer installations at the site of waste generation, which will solve the problem of waste transport or sanitary hazards. This goal also aligns to concept of zero waste cycle or agroecological system to sustain food production that inspired certain regulations.

Challenges and opportunities to water quality and human health

Challenges

In terms of soil health, 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 increased antibiotic resistant in the agricultural soil. However, along with the development of research, the side effects could be reduced. In Table 3, 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. Furthermore, the more opportunity possibilities will be discussed in the next section, "Opportunities."

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, manure-based 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 flow, 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 effective 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,

Table 3 Challenges and opportunities of using BBFs in ecosystem services

Challenges — solutions	Opportunities
• Antibiotic and microplastic residues — no direct application of BBFs	• Improve crop quality
• Toxicity of heavy metals — proper waste management	• Increase the uptake of micronutrients
• Pathogen exposure — sanitation process	• Promote soil biodiversity
• Salts accumulation — fertilizer management practices	• Help remediation process

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, e.g., bio waste, could offer another alternative to lower the risk of contamination to the environments (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. In addition, in the struvite samples produced from different methods and sources, the quantified hazards detected varied, thus indicating that production methods could be a large factor in the risk associated with wastewater-recovered struvite (Yee et al., 2019).

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 significantly 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 mineral 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 mineral fertilizer find their way to loss through leaching or runoff 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 product is needed to know the limit of BBF utilization.

Apart from the risks of BBFs use to soil health, basically there are some challenges that should be consider comprehensively compared to mineral fertilizer, such as transportation and production cost, social acceptance, and regulation. However, we are going to discuss the topic in the next section, "Future research perspective," as out of soil health topic.

Opportunities

Human health is the main priority of food production which depends on the food quality from farm field. Factors, such as soil related to imbalance fertilization or other detrimental management practices, affect the crop quality and productivity. Salts accumulation and heavy metal contents coming from fertilizers can be absorb by plants and affect the human health. Thus, BBFs production prioritizing hygienization could be expected as safe fertilizer.

Mineral 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 organo-mineral fertilizer increased the amount of crude protein in wheat grains, similar to that obtained after the application of mineral 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 and, hence, a potential increase in nutrient cycling. The capability of BBFs to improve soil biological properties is the advantage that mineral 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 mineral 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. The 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 biostimulation agent for enhancing remediation of oil-contaminated soils compared to natural attenuation (Liu et al., 2019). Moreover, compared to mineral fertilizer, the application of MBM at the rate of 1.0 to 2.0 t ha^{-1} did not lead to higher contamination of groundwater, while the increased rate supported mineral nitrogen and phosphate concentrations in groundwater samples (Szymczyk & Stępień, 2018). Similar result is shown by Silvasy et al. (2021) that split application of MBM reduced potential NO_3^- N losses by 20%.

Mitigation of climate change

Agricultural activities using BBFs have the potential to mitigate climate change due to the utilization of organic fertilizers over mineral ones and thus increase soil organic matter (SOM) content. Increases in soil organic matter/soil C content are highly beneficial from the standpoint of soil health and soil fertility and play a role in helping draw down atmospheric CO_2 concentration (Paustian et al., 2019). Moreover, the increase of soil organic carbon (SOC) is seen not only as a potential way of improving crop yield and quality but also as soil C sequestration. SOC concentration ranging between 1.2 and 1.4% in compost-amended treatments granted vegetable crops yields always higher than or similar to mineral fertilization (Morra et al., 2021).

The use of BBFs as organic fertilizers has some benefits for adaptation to climate change effects since it has greater water retention capacity than mineral fertilizers. Moreover, organic farming is more efficient in its use of nonrenewable energy, maintains or improves soil quality, and is less detrimental on water quality and biodiversity than conventional farming (Clark, 2020). The careful management of nutrient cycles in the soil is one of contributor in adaptation and mitigation of climate change.

In the case of climate change, fertilization, especially nitrogen, is the main issue because of the emissions generated by the production and application of fertilizers. Emissions from the production of mineral nitrogen fertilizers amount to about 1.75% of total EU emissions, while manure composting can significantly reduce nitrous oxide and methane emissions by 50 and 70%, respectively (Muller et al., 2016). However, in another point of view, LCAs have indicated that organic farming resulted in higher GHG emissions due to its lower crop yields and required significantly larger cultivation area to achieve the same crop production with conventional system (Clark, 2020; Foteinis & Chatzisymeon, 2016). In line with Chiew et al. (2015), digestion of the food waste and use of the digestate as fertilizer did not lower global warming potential compared to use of chemical fertilizers and incineration of food waste which has a better net contribution to primary energy. Therefore, the production of BBFs to support the productivity of organic farming by reducing GHG emissions should be developed through proper technologies and methods.

Future research perspective

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 the movement in the society. The use of mineral fertilizer has been ingrained with all of the advantages. On the other hand, bio-based fertilizers are expected to partly or fully substitute mineral 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 mineral 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 mineral 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 do 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 mineral 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 regulation 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).

Conclusions

Soil health has a broad definition, including the capability of the soil to provide a sustainable living ecosystem (plant, animal, and human) that is affected by fertilization. The use of bio-based fertilizers is expected to cover soil health problems. On the other hand, the production of mineral fertilizer needs high-intensive energy relying on minerals and fossils as raw materials. Energy alternative source in the form of BBFs is the potential to replace mineral fertilizers and solve the environmental issues caused by biological wastes. The development of BBFs production is challenging and promising at the same time since it could be a business opportunity and source of nutrients for plants. Thus, it will also push a comprehensive and integrated method that concurrently designs and manages sustainable agricultural and food systems using ecological and social concepts and principles. There is plenty of space for moving forward, but it requires an economic calculation to produce BBFs and social acceptance supported by policy maker to implement at a large scale. Assessing the techno-environmental performance helps to valorize the products in the long term. In the end, research about BBFs will need a huge approach outweighing the function as prospective fertilizer to support plant production.

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Data Availability The data used for this study are available upon request by contacting the corresponding author.

Declarations

Ethics approval and consent to participate Not applicable because the study did not involve humans.

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