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# Circulation of nutrients through bio-based fertilizer products: perspectives from farmers, suppliers, and civil society

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Closing nutrient cycles by bio-based fertilizer products (BFPs) can improve the environmental sustainability of food systems and facilitate a more circular economy. Although the theoretical potential for nutrient recycling has been explored in detail, BFPs still seldom replace mineral fertilizer products in practice. The aim of the present study was to explore the critical enabling and limiting factors for the use of BFPs as seen from the perspective of farmers, suppliers, and civil society. To this aim, qualitative interviews were conducted with seven conventional grain farmers, six suppliers of BFPs, and five representatives of civil society, limited to environmental non-governmental organizations. The presented results illustrate a mismatch between demand and supply. On the one hand, the interviewed farmers were only interested in using BFPs if they are practical to use, balanced with respect to nutrient contents, and potentially provide the same earnings as mineral fertilizers. Positive effects for soil quality were an important driver for many of the farmers. On the other hand, the suppliers of BFPs were generally not able to offer products that fulfilled the farmers' demands without economic losses, and they emphasized that they have faced several regulatory challenges. Representatives of regional civil society organizations expressed concern that new technical solutions could cause new environmental challenges, and that BFPs could enable further intensification of livestock production. The central-level representatives from the same NGOs, however, were positive about that BFPs can solve environmental problems. Policy instruments will be needed to increase the adoption of PFPs. Fostering BFPs' that contribute to a sustainable agriculture is important to consider when formulating these polices.

KEYWORDS

**circular economy, waste, demand, supply, civil society**

## 1. Introduction

Nutrient circularity is an important part of a circular economy. Nutrient imbalances in food systems can have negative effects on both agricultural productivity and sustainability, as well as on the quality of water recipients (Macdonald et al., 2011; Harder et al., 2021). The nutrient imbalance between world regions, as well as within regions, is contributed to by international trade in agricultural products, making recycling back to the origin of production challenging and leaving regions vulnerable to changes in the market (Nesme et al., 2018). On the national and regional levels, areas dominated by livestock production tend to accumulate an excess of nutrients, such as phosphorus (P), whereas areas primarily producing cereals and forage crops typically experience P deficits with a net export of nutrients. Cases of such nutrient imbalances at the national level are known in France (Senthilkumar et al., 2012), UK (Bateman et al., 2011), and Norway (Hanserud et al., 2016). More circular nutrient use can be achieved at the regional level by cooperation between farms, and at cross-regional levels by recycling nutrients in waste resources back to agriculture through the production and use of bio-based fertilizer products (BFPs) (Macdonald et al., 2011; Fernandez-Mena et al., 2020).

This paper uses nutrient circularity through BFPs as a case to illustrate the socioeconomic possibilities and barriers for achieving a circular economy. Previous research on the circular economy has largely neglected business, social, and economic perspectives (Lieder and Rashid, 2016; Zink and Geyer, 2017) and the dynamics between bioeconomic innovations, policy instruments, markets and the civil society are not well understood (Gregson et al., 2015; Ho et al., 2022; Spekkink et al., 2022). Socioeconomic challenges include economic and financial viability, market and competition, standards and regulation, as well as cultural issues (Van Loon et al., 2018; Bressanelli et al., 2019; Duquennoi and Martinez, 2022). These challenges are highly relevant for the supply of and demand for BFPs, as several technical, economic, cultural, and regulatory issues need to be considered before achieving organic waste recycling through BFPs (Flotats et al., 2009; Ekane et al., 2021).

Several studies have suggested solutions for how to increase the circulation of nutrients at different spatial scales (Jedelhauser et al., 2018; Cobo et al., 2019; Withers et al., 2020). These studies tended to focus on the technical solutions for nutrient cycling through the processing of organic waste resources, such as animal manure and food waste into BFPs. Even though the theoretical potential for nutrient recycling has been explored in detail, BFPs seldom replace mineral fertilizer products in practice. Several authors (i.e., Metson et al., 2015; Barquet et al., 2020; Zhao et al., 2020) underline that more research is needed on how market conditions, policies, preferences and values influence the production and use of BFPs. Hence, there is a need for studies of socio-economic barriers and opportunities for the production and use of BFPs, as the success of BFPs in the circular economy depends on the development and supply of these products by suppliers and the use by farmers. Without producers that supply BFPs and farmers that demand BFPs, adoption of BFPs cannot be realized.

Previous studies have shown that farmers' adoption of agricultural technology depends on a number of factors, including information, perceived benefits of an innovation, farm or farmer characteristics, social networks, the economic environment, attitudes toward new technologies, risks, and the environment (Pannell et al., 2006; Prokopy et al., 2008; Maertens and Barrett, 2013; Dessart et al., 2019; Chavas and Nauges, 2020). A handful studies have examined farmers' preferences for using BFPs in a European context. Case et al. (2017) examined Danish farmers' adoption of and attitudes toward BFPs. They found that two-thirds of the farmers were interested in using BFPs produced from manures and 20% were interested in using BFPs produced from urban waste (i.e., sewage sludge and municipal solid waste-based products). Farm and farmer characteristics, such as type of production (i.e., organic or conventional) and age influenced the likelihood of adopting BFPs in the future. Younger farmers were more interested in processed manure and organic farmers were more interested in BFPs produced from urban waste. The most important hurdles for using BFPs among the surveyed Danish farmers were odor nuisances toward neighbors, uncertainty related to nutrient content, difficulty in planning, and difficulties in spreading BFPs. Improved soil structure was seen as the most important advantage of using BFPs. Tur-Cardona et al. (2018) conducted a survey among farmers in seven European countries. The results indicated that, across the different countries, the farmers preferred concentrated BFPs that can be purchased at a lower price than mineral fertilizers and have a reliable nitrogen (N) content. Other qualities, such as the presence of organic carbon (C), hygienization of the BFPs, and fast release of nutrients, were important for the farmers in some countries. The results from this study imply that, for BFPs to be preferred by farmers, they need to have similar characteristics as mineral fertilizers in addition to being cheaper (~65% of the price of mineral fertilizers). A survey among Washington State farmers in the US (Hills et al., 2021) pointed to the need for data from field trials and data on N release from BFPs to increase famers' willingness to adopt these products. Though a few studies have already examined farmers' preferences and expectations for BFPs, the study of suppliers' opportunities and challenges regarding the production and marketing of BFPs is limited (Bressanelli et al., 2019).

Velenturf and Purnell (2021) underline that the civil society should be involved in the design and implementation of a circular economy to ensure a sustainable circular economy. Civil society could play an important role in terms of influencing regulations and policies, but also as an important actor that could directly or indirectly address how businesses and consumers should or ought to act (Ghisellini et al., 2016; Jørgensen and Remmen, 2018). The role of the civil society in advancing a circular economy is, however, rarely acknowledged in the literature (Ho et al., 2022; Spekkink et al., 2022). Hence it becomes important to study the perspectives of the civil societies with regard to BFPs.

The literature review shows that, while a few studies have examined farmers' requirements for BFPs, information on suppliers' and civil society perspectives is limited. Most studies also tend to focus on supply or demand actors. Therefore, the objective of this paper was to explore the critical enabling and limiting factors for production and use of BFPs to secure nutrient circularity in the economy, as seen from the perspective of supply, demand, and civil society actors. To support the main objective, we looked into three research questions: (1) What are farmers' perspectives on BFPs and what kind of product properties are important for farmers adoption of BFPs?, (2) What kind of opportunities and challenges do suppliers face int. their production and sale of BFPs?, and (3) How do representatives from civil society, in terms of environmental NGOs, perceive the role of BFPs in the circular economy?

## 2. Materials and methods

### 2.1. The case: norway

In this study, we used Norway as a case. Norway is currently the world's biggest producer and exporter of farmed Atlantic salmon and rainbow trout (Minstry of Trade Industry and Fisheries, 2021). A distinctive characteristic of Norway is therefore that it needs to deal with organic waste originating from aquaculture activities, in addition to more common organic waste, such as animal manure, food waste and sewage sludge.

In 2019, Norwegian aquaculture was responsible for the losses of 66.000 ton (t) N and 14.000 t P to the sea (Broch and Ellingsen, 2020). Nutrient losses from Norwegian aquaculture are hence in the same order of magnitude as the amount of N and P annually applied to Norwegian land in the form of mineral fertilizer (99.000 t N and 8,000 t P; Norwegian Food Safety Authority, 2023) or as animal manure (12,000 t P; Hamilton et al., 2016). Operators of land-based fish farming are required to clean the wastewater for fish sludge (i.e., feed residues and faeces) to avoid pollution of ecologically vulnerable coastal areas. Even though in 2019 collected fish sludge only represented 102 t P (Broch and Ellingsen, 2020), increasing amounts of fish sludge are expected with the ongoing trend for moving post-smolt production and salmon farms from open fish farm systems in the sea to land and with (semi-)closed production systems in the sea.

Not only fish sludge, but also livestock manure is mainly produced on the Norwegian west coast, whereas the south-eastern part of Norway is characterized by grain farming without livestock production. A possible solution to this geographical nutrient imbalance is the production and use of BFPs based on fish sludge or manure. Dewatered and dried fish sludge from fresh-water based hatcheries is already used in the production of BFPs. Some farmers are separating manure for transportation of the solid fraction but markets for solid manure fractions are currently immature.

Food waste and sewage sludge represent smaller amounts; 2,600 t P and 1900 t P, respectively (Hamilton et al., 2016). Whereas some European countries (e.g., Switzerland) have prohibited the direct use of sewage sludge on agricultural soil (Schoumans et al., 2015), in Norway around 60% of sewage sludge is returned to agricultural soil as soil amendment (Hamilton et al., 2016), mainly due to its positive effects as soil conditioner and as liming material (Refsgaard et al., 2004).

## 2.2. Research methods

Qualitative research methods were used with the aim to acquire a deeper understanding of the motivations and barriers involved in using or producing BFPs. Though choosing a qualitative research strategy restricts the possibility of generalizing to the wider population, it opens up the possibilities to gain a more comprehensive understanding of the nuances that influence decision-making (Bryman, 2016). Norwegian farmers often have limited or no familiarity with BFPs; therefore, qualitative interviews are better suited for explaining what BFPs are and understanding the farmers' thoughts on using these products.

For all the interviews we applied a semi-structured interview method, or what Burgess (1984) referred to as a 'conversation with a purpose'. We developed a list of open-ended questions and topics to provide the respondent to reflect upon in a dialogic conversation with the interviewer.

The interviews were recorded and notes were taken during the interviews. The interviews were not transcribed in detail but listen through several times. The main reason for that was that we wanted to bring the tone and nuances from the interview closer to the analysis and not just rely on the transcripts. Three of the researchers in the project listened through each interview separately several times and bookmarked the audio file each time to mark the most relevant part of the interview. Later, we compared our findings, discussed our bookmarks, and how we interpreted and understood the different interviewees' perspectives and perceptions. In this process, part of the interviews was transcribed for further coding and other part was coded directly based on the audio recording. The point of having three researchers working separately before comparing each other's findings was to enhance the trustworthiness of the analysis. It was a process of what Lincoln and Guba (1985 p. 308) describe as "exposing ourselves to peer in a manner paralleling an analytical session and for the purpose of exploring aspects of the inquiry that might otherwise remain only implicit within the inquirer's mind."

To meet another of Lincoln and Guba (1985) criteria for enhancing trustworthiness, we also applied member checking, which Lincoln and Guba (1985) assorted is the most important form of credibility check. This allowed us to check our interpretation and further investigate the informant's preferences and perspectives. Finally, a summary of the most important findings was set up in a table.

### 2.2.1. Interviews with farmers

In 2018, we performed interviews with seven conventional grain farmers to examine the farmers' willingness to buy and use BFPs. All of the farms were located in the south-eastern part of Norway, which is dominated by grain production. All interviews were performed on their farms, and the interviews were audio-recorded. Three of the farmers were identified and suggested by the local agricultural authorities as forward-leaning farmers who in the past had used sewage sludge on their fields. The remaining farmers were randomly selected among all grain farmers in one municipality. By using both random and purposive sampling, we ensured to include at least some farmers who could potentially be interested in these products. By this we could gain a better understanding of how more representative farmers would respond to these products. The interviews with the farmers were divided into two parts, the first part fairly more open than the second part, to get the farmers general thoughts on BFPs. Here the farmers were guided as little as possible and where free to bring in their own perspectives. For the second part we developed a bit more structured interview guide, still semi-structured though, that included a presentation of five different BFPs. For the five different BFPs, the farmers were informed about the nutrient content and balance, P availability, organic matter content, method of spreading, odor, and what types of waste resources they were produced from (see supplementary material for more details). The choice of products was based on variations in these aspects. Two of the products were sold on the Norwegian market, whereas the others were in the pipeline when the interviews were performed.

### 2.2.2. Interviews with suppliers

In 2018 and 2020, qualitative, semi-structured interviews were conducted with suppliers of six different BFPs. The purpose was to gain a more thorough understanding of what kind of opportunities and challenges suppliers of BFPs face. The suppliers were selected based on advice from research colleagues with good knowledge of the sector to include the most important actors. Two of the suppliers were located in the south-western part of Norway and four in the south-eastern part of Norway. A semi-structured interview guide was developed to ensure that relevant aspects concerning socioeconomic drivers and hinders were covered. Five of the interviews were conducted by phone and two conducted in person (total seven interviews, and two concerned the same BFP). The suppliers were given the opportunity to comment on and update the text about their company prior to the submission of the paper.

#### 2.2.3. Interviews with representatives of civil society

As BFPs mainly concern resource and environmental issues, we chose to interview five representatives from the most important member-based environmental NGOs in Norway. The interviews were carried out in March 2019. To include various perspectives, we interviewed both national and regional representatives. The regional representatives were recruited from Rogaland, the region with the highest livestock density in Norway. The five interview subjects represented Spire, the youth organization of an environmental and development organization (one at the central level and one from the regional level), Young Friends of the Earth (one from the regional level), and Friends of the Earth (one at the central level and one from the regional level).

## 3. Results

### 3.1. Farmers

The purpose of this section is to present the results from the qualitative interviews regarding farmers' perspectives on BFPs and what kind of product properties thar are important for their adoption of BFPs. Table 1 presents the main characteristics of the farmers who were interviewed. The farmers varied in age, gender, and whether they were full-time or part-time farmers. R1 was a 52-year-old full-time grain farmer who recently bought a farm from his uncle. He had previously worked as a building contractor. He had a strong interest for farming and food safety. R2 was a full-time grain and pig farmer in his 50s who had been farming since the 1980s. His pig manure made up a relatively small part of the total need for nutrients. He was satisfied with his economic situation, but he worked many hours and hardly had any leisure time. He enjoyed farm work and to be his own master. He was critical of other farmers who expanded their farm as this means less time for adequate management of crops and more transport. R3 was a young part-time grain farmer with young children, and she worked as a nurse. Given this situation, she had limited time for farming, and it was important that her field operations were as efficient as possible. She had recently taken over the farm and she found it meaningful to contribute to national food production. R4 was a part-time grain farmer in his 50s who worked as a teacher. He had been farming for more than 20 years and was concerned about environmental sustainability, and he had some interest in organic farming. R5 was a 53-year-old full-time grain farmer. He was strongly concerned about soil quality, and he had not plowed for 20 years. R6 was a 60-year-old grain farmer. During the growth season, he is a full-time farmer, but he works off the farm during the winter season. R7 (46 years old) was also a grain farmer. The farmers who were recruited by purposive sampling (R5-R7) had experience using sewage sludge as a soil amendment. The other farmers had heard of farmers who used sewage sludge, but they were unfamiliar with BFPs.

#### 3.1.1. Product characteristics and price preferences – BFPs should be fairly similar to mineral fertilizers and improve soil quality

Improved soil quality from BFPs was valued by most of the farmers (R1, R4-R7). They underlined that there is a great need for more organic matter in the agricultural areas dominated by monoculture grain crops. R1 told that organic matter content in the soil is a challenge for his farm. When he was a kid, half of the infields were grassland and they spread manure regularly, but this is more than 40 years ago. Organic material was, however, not important for one of the farmers (R2) as he had applied pig manure to his soil for several years without experiencing any improved soil quality. The organic matter content in BFPs was also of less importance for R3.

Balanced nutrient content and certainty about the nutrient content in BFPs was crucial for several of the farmers. R3 pointed out that without information about the nutrient content, she would not be able to fulfill the official requirements for a fertilizer plan. Many of the farmers did further underline that it was essential that BFPs could be spread by their combination seed drill to avoid additional operations in the spring and extra work. R2 was concerned about the amount of BFPs he had to apply on his fields compared to mineral fertilizers, as well as extra work regarding spreading and increased soil compaction. Two of the farmers (R4 and R5) were, however less concerned about extra work and need for additional operations or spreading equipment.

Farmers willingness to pay for BFPs varied. Some of the farmers underlined that BFPs need to be cheaper than mineral fertilizers, as these products would imply extra work and challenges. Others might

TABLE 1 The main characteristics of the farmers who were interviewed.

| ID | Production | Arable land | Part-time/Full-time | Age | Gender | Sampling |
|---|---|---|---|---|---|---|
| R1 | Grain and some sheep production | 178 daa | Full-time | 52 | Male | Random |
| R2 | Grain and hog production | 512 daa | Full-time | 55 | Male | Random |
| R3 | Grain | 300 daa | Part-time | 30 | Female | Random |
| R4 | Grain | 185 daa | Part-time | 57 | Male | Random |
| R5 | Grain | 3,500 daa | Full-time | 53 | Male | Purposive |
| R6 | Grain | 3,000 daa | Part-time | 60 | Male | Purposive |
| R7 | Grain | 3,600 daa | Full-time | 46 | Male | Purposive |

Daa, decare.

be willing to pay a premium price if BFPs were beneficial to their yield and long-term soil quality.

### 3.1.2. Variations in environmental engagement

There was variation among the farmers when it came to their environmental motivation for being interested in BFPs. R4 was willing to pay a premium price for BFPs due to environmental benefits and said that "mineral fertilizers may not be sustainable in the long run," and that BFPs "could definitely be interesting if I could use it and be an organic grain farm." However, environmental aspects were not so important for R1-R3's overall assessment of using BFPs on their farm. Most of them did, however, value using resources that otherwise would have been wasted. R2 said that "we need to do something about the excess of nutrients in the western part of Norway. We cannot just throw it." He did, however, question whether "it is good for the environment to transport the BFPs from west to east."

All three farmers who had experience using sewage sludge (R5-R7) were very concerned about soil quality and the constantly shrinking humus content in the grain areas in southeastern Norway. They referred to reports from the media and various websites that discussed the poor soil quality in countries such as the Netherlands, Germany, and even England and thought that similar concerns were relevant for the grain areas in Norway.

### 3.1.3. Trust in product safety

Safety concerns were unimportant for the overall assessment of BFPs for farmers R2-R4. R3 and R4 emphasized that they trusted the safety assessment by experts and authorities. R3 further emphasized that BFPs need to be controlled by the authorities and that she wanted to know "what it comes from." Although R2 said that he had heard that sewage sludge contains "some substances that are not good for the soil," these concerns were not important for his assessment of whether he would use BFPs.

Compared with farmers R2-4, R1 was concerned about the safety of BFPs, especially products based on sewage sludge and fish sludge. He was afraid that, by using BFPs from sewage or fish sludge, "we will impose something on future generations – we will not be able to get it out of the ground again." He also had some distrust of scientific safety assessments. He emphasized that "research is based on short-term studies, they do not look 50 years ahead. We may not know if it is safe until 50–100 years have passed," and that "those who pay for research get the answers they want." He emphasized that Norwegian agriculture must "focus on safe food" and was afraid that agriculture may "have a reputation problem" if they used these products. When it comes to sewage sludge, he was worried that "metals and medicines are left in the soil." Regarding fish sludge, he said "I have heard a lot of strange things about these fish farms." He was not skeptical of products based on livestock manure: "Livestock manure is not completely clean – but some of the cleanest you can get." Despite this skepticism, R1 still concluded that you "just have to trust it," and that "as long as they are approved, we will use it if it is better than what we do now."

R5, R6, and R7 all hoped there would be less environmental risk connected to an approved commercial BFP than to the sewage sludge they used today, but the product must be well-documented, and the approving authorities must be totally impartial. If this is in place, and if the BFP could compete on price with the combination of sewage sludge and mineral fertilizer, they would all choose BFP.

### 3.1.4. Agricultural information sources important for farmers fertilizer decisions

Advice from the Norwegian Agricultural Advisory service (R1, R4, and R6), the local agricultural authorities (R4, R5, and R7), and the local farm supply cooperative (R3) were important for the farmers' interest in BFPs. R4 emphasized that "the agricultural advisory service comes with recommendations for fertilization and spraying - which I often follow slavishly." R5, R6, and R7 all had great respect for the unique knowledge at the advisory service, as well as the agricultural authorities and appreciated the opportunity to discuss issues with them.

### 3.1.5. Concern about unpleasant odor for neighbors by existing users

All the farmers who had experience using sewage sludge (R5-R7) were concerned about the unpleasant odor. They hoped an approved BFP would solve this problem and stated that, in the long run, farmers could not stand more negative publicity in the media on odor from sewage sludge. The farmers who were unfamiliar with sewage sludge (R1-R4) were not concerned about unpleasant odor for neighbors from BFP.

## 3.2. Suppliers

The purpose of this section is to present the results from the qualitative interviews with suppliers of BFPs regarding the opportunities and challenges they face in their production and sale of PFPs. Table 2 provides an overview of the six different producers of BFPs that were interviewed. Half of them were privately owned, and the other half were owned by municipalities. They produced BFPs based on sewage sludge, wastewater, fish sludge, food waste, and manure.

### 3.2.1. S1: Pelleted BPFs from fish and sewage sludge – demand from abroad

S1 markets pelleted organic fertilizers based on fish sludge in various combinations with other nutritive ingredients including sewage sludge (biosolid). The supplier of the main fraction of fertilizers to S1 is a municipality-owned wastewater treatment plant that has incorporated a fertilizer line as part of the treatment solution for their biosolid.

S1 markets and sells fertilizer products in Vietnam. Shipping rates reflect the need to fill in return capacity to Asia. The farmers in Vietnamese markets highly value fertilizers with a high content of organic matter due to their tropical climate. As P demand is low Norway, and because of the limited amount of arable land in Norway, the Norwegian market is of minor commercial interest for this company.

Initially, S1, in collaboration with the wastewater treatment plant, sought to develop and sell BFPs for use by Norwegian grain producers. S1 balanced the grain fertilizers in terms of N, P, and potassium (K) content. The fertilizers provided reliable results compared to conventional mineral fertilizers. However, S1 faced introductory technical issues related to pellet quality. In the beginning, pellets had to meet the quality criteria for use in combination seed drillers. Too much dust or irregular pellet size occasionally caused operational problems when fertilizing. The willingness of farmers to pay were low

TABLE 2 Suppliers: ownership, raw materials, and (possible) customers.

| ID | Ownership | Raw materials | Product | (Possible) customers |
|---|---|---|---|---|
| S1 | Private | Fish sludge and sewage sludge | Pelleted organic fertilizers | Farmers in Vietnam |
| S2 | Municipality | Wastewater | Struvite | Organic farmers |
| S3 | Private | Poultry manure | Pelleted organic fertilizers | Conventional and some organic farms in Norway |
| S4 | Private | Poultry manure, fish sludge (only for conventional farming) | Pelleted organic fertilizers | Mainly organic farmers in Norway |
| S5 | Municipality | Food waste | Liquid digestate | Conventional and some organic farms in Norway |
| S6 | Municipality | Food waste and manure | Liquid digestate | Conventional farmers in Norway |

for a new organic alternative. Moreover, since it took a long time to establish the necessary dispensation in the fertilizer legislation, S1 chose to develop alternative markets outside Norway.

### 3.2.2. S3: Pelleted fertilizers from poultry manure – demand from conventional ruminant farmers

S3 is a company that is mainly owned by an agricultural cooperative. They are located in the region with the highest livestock density in Norway and offer pellets based on poultry manure. Some of the products are enriched with K, urea, and various minerals. Their BFPs are mainly sold to conventional farmers, but they also market some products for organic farming. The fertilizer product is designed for use in grazing areas and meadows. They receive payment from poultry farmers for receiving and using their manure. These farmers have more manure than they are allowed to use on their fields.

Their BFPs were first approved for use in Norway and then for use in the EU. The representative for the company emphasized that the approval process in Norway was costly and time-consuming. The company considered markets outside Norway, such as Sweden and Denmark, as promising because hardly any similar products are available in the EU. Some years ago, the company received a request for sales to Vietnam. However, the Farm Unions in Norway were skeptical toward export of fertilizer products made of Norwegian manure due to qualms about decoupling the livestock production from the land-and soil-resources on the farms.

The representative for the company underlined that the absence of country-of-origin labels on BFPs implies that costumers, both commercial and private, have no information and low awareness of whether the marketed BFP is of Norwegian origin or imported. Norway currently imports poultry manure from more than 20 different countries, and S3 expected an increase in demand if costumers became aware of the origin of the BFPs.

### 3.2.3. S2: Struvite from wastewater – demand from organic crop farmers

S2, a municipal wastewater treatment company, has developed a process to remove P from wastewater without using chemical precipitation agents. The P is recovered in the form of the salt struvite, which can be used directly as fertilizer or as an ingredient in fertilizer products. Their production of struvite at the wastewater treatment plant has been at the forefront of regulatory development, as they were the first plant in Norway that produced struvite. It was unclear whether it should be regulated as an organic or inorganic substance. After an extensive dialog with the Norwegian Food Safety Authority, struvite was approved as an inorganic end-product with organic origin (i.e., sewage sludge).

The EU approved struvite for use in organic farming in 2022, and the company has entered into an agreement with a commercial player who will sell the struvite. They have chosen to focus on the organic market, as they expect a greater willingness to pay because organic farmers have fewer alternatives from which to choose.

The company representative suggested that, if authorities decide to require a given share of recycled P in fertilizer products, the demand for BFPs could increase. He further emphasized that the best way forward to make recycling of P profitable for wastewater treatment plants is to ensure economic support for investment in necessary technologies.

### 3.2.4. S4: Pelleted organic fertilizers from various waste resources – mainly demand from organic farmers

S4 produces BFPs based on poultry manure from local farmers. They are located in the southeastern part of Norway where farming is dominated by grain production. The fertilizers are mainly sold to organic farmers for cultivation of grass and grains, but also for potato, apples, and plums. They also market a hybrid BFP for conventional agriculture. The hybrid fertilizer is based on 50% organic fertilizer and 50% mineral fertilizer. Fish sludge is one of the raw materials in this fertilizer. Hybrid fertilizer is chlorine-free and has long-acting N. The fertilizer helps to maintain and increase valuable micro-life in the soil while providing a high yield. There is great interest in this fertilizer, and S4 is experiencing a significant increase in sales of this product.

The representative for the company emphasized that, to increase the use of BFPs among conventional farmers, it is crucial that the authorities establish incentives so that these products can compete with mineral fertilizers. He also expressed some frustration with the Norwegian regulation on organic production, which does not allow the use of fish sludge in organic agriculture. Fish sludge is a waste product that the fish farming industry needs to get rid of, and this resource has attributes that are well suited for producing BFPs that are in demand by farmers. He underlined that "it is important that the authorities do not apply old regulations and old principles for approval on new waste resources and raw materials in the circular economy. The r0egulations are not adapted to the new economy."

### 3.2.5. S5: Liquid digestate from food waste – used by surrounding farmers

S5 is owned by one of the larges municipalities in Norway. They have established a biogas plant for food waste in another municipality in southeast Norway with large grain areas. They use food waste mainly from their municipality, but they also receive some minor fractions of food waste from other municipalities and business actors. They produce a liquid anaerobic digestate that is sold to local farmers for use as fertilizer on grain and grass areas.

The liquid BFP requires adapted spreading equipment, and the dry matter content is low. Therefore, it takes much longer and is more expensive for the farmer to spread liquid fertilizer than mineral fertilizers. To compete with mineral fertilizers, S5 only charged the farmers for the net fertilizer value, subsidized both transportation and spreading costs, and paid farmers to store the liquid product during the winter season. Thus, the company lost money on their sale of the liquid fertilizer product.

When S5 started to offer the liquid BFP in 2015, there was little interest in the product from farmers. However, S5 did emphasize that they currently have a stable recipient group and increasing interest from farmers. Some of the customers were organic farmers. The liquid fertilizer was regularly tested for determination of the level of cadmium content by a third party. The results determined whether the fertilizer could be used for organic farming, and the farmer received a declaration that could be used in the fertilizer plan.

#### 3.2.6. S6: Liquid digestate from food waste and manure – used by surrounding conventional farmers

S6 is owned by a municipality in the southeastern part of Norway. One of their biogas plants produces a liquid anaerobic digestate from food waste and manure from cows and pigs. The liquid BFP is offered to local conventional farmers (mainly grain farmers) for free, and the company has a long list of interested farmers. Potential receiving farmers were contacted in the planning phase and this secured disposal of their BFPs. The delivery is organized by 10-year contracts. The farmers have their own storage tanks, and the BFP is spread with hoses.

The representative for the company underlined that the benefit of manure as an input for the biogas production is limited compared to food waste. However, they can reduce their water consumption by using animal manure. Livestock farmers receive a subsidy for delivering livestock manure to the biogas plants, and this subsidy was important for the company's use of manure. Whether there should be a subsidy and how large the subsidy should be is decided for one year at a time. This made it difficult for the company to make long-term decisions.

Their liquid BFP has not been approved for organic farming because the zinc concentration on dry matter basis is too high according to applicable regulations. The company representative did, however, emphasize that it is problematic that Norwegian fertilizer regulation is based on the level of heavy metals per kilogram of dry matter as spreading of liquid fertilizers implies small amounts of dry matter per hectare. They emphasize that it would make more sense to regulate based on added quantity of heavy metals per area.

### 3.3. Civil society - environmental NGOs

The purpose of this section is to present the results from the qualitative interviews with representatives from civil society organizations regarding they perceive the role of BFPs in the circular economy.

Although there was overlap between all three environmental organizations we interviewed, the distinction seems to be between the regional and central representatives. The central representatives of both Spire and Friends of the Earth were not only positive, but also optimistic in their expectations of BFPs. Friends of the Earth pointed out that "… this is what the entire environmental movement has been hoping for, we become optimistic when commercial actors try to make a difference by solving environmental problems." The central representative for Spire also joined this hope and placed themselves among those who acknowledge the principle of ecological modernization, where the key to solving environmental challenges lies in making it economically - or commercially - interesting to develop environmental solutions. Both Spire and Friends of the Earth believe that there is a need for more organic material in the grain area in both the eastern part of Norway and elsewhere; they also believe that such products can reduce not only the use, but also the dependence on mineral fertilizers. Therefore, at a central level, two of the most important member-based environmental organizations in Norway are very optimistic about the fact that BFPs can contribute to environmental improvement in the grain area while helping solve an extensive waste problem.

Among the regional representatives of Spire, Young Friends of the Earth, and Friends of the Earth that were located in the region with the highest livestock density in Norway, there was clear skepticism toward BFPs. The skepticism seems to rest on two pillars; one can be said to be rooted in a historical perception that technological solutions often create new challenges, but the other pillar is about "knowing your neighbors," as the representative for Young Friends of the Earth expressed it.

To take the last pillar first – knowing your neighbors – it is partly about the perceptions of the local farmers from this region as innovative and oriented toward intensive farming. The main argument for all three regional representatives was that, if we come up with a technical and logistical solution for drying and pelletizing manure from this region in order to export the fertilizer eastward in Norway, it will, in the long run, imply that the spreading area requirement for manure is no longer a restriction to increasing the livestock density, which in practice is one of the few restrictions that prevents further intensification of livestock production in this region.

The second pillar on which the skepticism rests, the perception that technological solutions often create new challenges, reveals a certain mistrust that the control regimes are unbiased and thorough enough. They believed that we are often so eager to get the products on the market, and thus get investor capital in, that we release the products before they have been thoroughly tested for adverse consequences. They were particularly skeptical of BFPs produced from fish sludge from the aquaculture industry, a sector that all three regional representatives considered as not particularly trustworthy.

## 4. Discussion

### 4.1. Farmers' perspectives on BFPs

The farmers varied somewhat in their response to BFPs. Most of them expressed that BFPs needed to be fairly similar to mineral fertilizers and provide the same earnings as mineral fertilizers for them to be an attractive alternative. Some of the farmers were, however, less concerned about extra work and need for additional operations or spreading equipment. Improved soil quality was important for many of the farmers and some of them were potentially willing to pay a premium price for increased organic matter content in their soil. Our results also indicated that small famers might face more obstacles, if they cannot use the spreading equipment they already use.

Most of the farmers trusted the safety of the products if they were approved by the food safety authorities. One of the seven farmers did, however, not fully trust the safety of swage and fish sludge. Given that fish sludge constitutes on of the most important waste resource for BFPs this might imply some challenges for improved nutrient circularity. In general, we found no strong environmental or intrinsic motivation to use BFPs among the farmers although some of them found it meaningful to use resources that otherwise would have been wasted.

## 4.2. Suppliers' perspectives and experiences

The suppliers of BFPs in Norway did to a limited extent manage to sell their products at a price that can cover the production costs. Several of the suppliers we spoke to sold mainly to organic farmers (S4) or planned to sell to organic farmers (S2), or they gave away or sold at the same price as mineral fertilizers (S5, S6) to conventional farmers or exported (S1). Of the private companies, only S3 had succeeded in making a product that is mainly sold to conventional farmers in Norway. This company received payments from the farmers that delivered manure to them. However, it has only been since 2021, when the price for mineral fertilizers increased, that this company has had positive earnings. Organic farmers, especially those without livestock, have a higher willingness to pay for BFPs because they have fewer alternatives to choose from, and the price of mineral fertilizers does not limit their willingness to pay. The organic agricultural land in Norway is quite limited and producing BFPs only for this market may imply the suppliers cannot take advantage of economies of scale. Thus, our findings imply that economic challenges are a crucial barrier for increased supply and use of BFPs in Norway.

Different regulatory barriers affected the suppliers' possibilities to produce BFPs. They emphasized that it is of vital importance that the authorities avoid using mismatched regulations for utilization of new resources and raw materials. The process for approving a new BFP is often time-consuming and costly. Inconsistencies in the regulation of organic fertilizer products were also emphasized.

## 4.3. Civil societies' perspectives

Including the voices of civil society in our study illustrates some of the dilemmas that are involved when facilitating a circular economy, particularly the tension between technological optimism and technological skepticism. The central representatives from the civil society organizations were very optimistic about the fact that BFPs can contribute to environmental improvement in the grain area while helping solve an extensive waste problem. Many of the regional representatives on the other hand were worried that there could also be cases in which BFPs legitimize production methods that could be unwanted by society. BFPs produced by manure enable intensive livestock production and decoupling of food production from the land resources on farms. Some of the representatives from civil society underlined that an alternative to BFPs from manure would be to spread the livestock production across more of the country. This view is also supported by representatives from Norwegian Farm Unions (Nationen, 2017).

It is interesting to see these differences between the central and the regional representatives from the environmental organizations. Confronting the respondents with our findings the central representatives did not want to speculate on why they had these different views. The regional representatives on the other hand talked about the advantage of 'being close to the practice field'. They draw up a picture that the representatives at the central level do not see what is going on locally and they are not close enough to neither the agri-industry nor the aquaculture industry. We do not have strong enough data to dig deeper into this, but it is for sure a topic for further investigation.

## 4.4. The relationships between actors and BFPs adoption

Lieder and Rashid (2016) and Yalcin and Foxon (2021) underline that only a comprehensive framework that is jointly supported by all stakeholders can support successful circular economy implementation. Our results show that to some extent there is currently a mismatch between some of the BFPs that is supplied by the producers and the product properties that are demanded by the conventional farmers. Increased dialog between farmers and producers of BFPs in their product development might increase the adoption of BFPs. One of the suppliers did for example contact potential receiving farmers in the planning phase of their biogas plant and this secured disposal of their liquid digestate.

It is also important to acknowledge the role of different farm advisory services. Several of the farmers expressed that the information provided by the Norwegian Agricultural Advisory service, the local agricultural authorities, and the local farm supply cooperative (R3) was important for farmers' interest in using BFPs. Therefore, it is important that these actors are aware of the pros and cons of using BFPs for farmers.

When it comes to different value-perspectives and perspectives on the use of different waste resources we observe both convergence and divergence between the different actors. Some sort of technological optimism was shared by the suppliers, the national civil society actors, and most of the farmers. The regional civil society representatives and one of the farmers were, however, worried that technological solutions often create new challenges, and they shared some distrust in the fish farming industry and the safety of using fish sludge. While the farmers had great trust in the safety of using livestock manure, the regional civil society actors were concerned that BFPs from manure would enable increased intensification of livestock production. This value divergence might pose some barriers for nutrient circularity through BFPs.

## 4.5. Policy implications

Geissdoerfer et al. (2018) emphasize that the private business often is given a crucial role in the transition to a circular economy. The case of BFPs in Norway illustrates, however, that private initiatives will not be sufficient to enhance nutrient circularity, given current technologies. A crucial question is therefore what could be done to stimulate production processes that are beneficial for circularity, but that do not provide satisfactory earnings within the current institutional structures. Institutional changes, in terms of government regulations and policies can be important strategies for realizing a circular economy embracing a wider use of BFPs.

Firstly, our results on farmers preferences indicate that it is important to extend current regulations by requirements for clear documentation on plant availability of nutrients in BFPs so that the farmers know their effects as fertilizer.

Secondly, it is important to develop policies that are targeted to the recycling of nutrients from each of the different types of waste resources. In Norway, fish sludge is one of the most important waste resources, and operators of land-based fish farming are currently only required to clean the wastewater before discharge. There are, however, no guidelines on how to utilize the collected fish sludge. Extending current regulations by requirements for nutrient recycling might enhance the production of BFPs from fish sludge. An important barrier to recycling fish sludge as fertilizer is the prohibition in organic farming both in Norway and in the EU. This is mainly due to lack of safety studies on this rather new product instead of actual risk findings. The most important hinder to the reuse of nutrients in fish sludge is, however, challenges related to its collection from offshore fish farms. A combination of technological innovations and policy instruments needs to be in place before this can be achieved. Excessive animal manure is more likely to be efficiently recycled than fish sludge, as policies for stricter requirements for manure application per hectare of arable land are already in the pipeline (Norwegian Agricultural Authority, 2021). This will provide incentives for reduced livestock density and/or production of BFPs from manure. Sorting and material recovery of food waste has in Norway been mandatory since Norwegian Food Safety Authority (2023), and food waste is being processed at biogas or composting plants with digestate and compost as resulting fertilizer products. Sewage sludge is currently mainly used as a soil amendment, and policies that can stimulate the production of fertilizer products based on sewage with the potential to replace mineral fertilizer could contribute to facilitate nutrient recycling.

Thirdly, general policies that address nutrient circularity are needed. The government has initiated an examination of the feasibility of a sale requirement for secondary P, i.e., that seller of fertilizers make sure that a given share of the total amount of P sold per year consists of secondary P. This was also suggested by one of the suppliers in our study. Important questions included which types of actors, i.e., the producers of mineral fertilizers or fertilizer suppliers that this requirement should apply to. Other general suggestions from the suppliers included country of origin labeling of BFPs, more stable and predictable economic policy instruments as well as fertilizer regulations that are adopted to the circular economy.

## 5. Conclusion

This study illustrates some of the challenges involved in the development of a circular economy, using nutrient cycling with BFPs in Norway as a case. The interviewed farmers had little experience with and knowledge of BFPs. However, most of the interviewed farmers showed an interest in BFPs, given that they are practical to use, balanced with respect to nutrients, and provide the same earnings as mineral fertilizers. As the most important drivers for farmers' adoption of BFPs, we identified potential for increased organic matter content in their soil and trust in the safety of products, if approved by the food safety authorities. However, our results show that the supplier of BFPs only to limited extent manage to produce BFPs that fulfill the expectations of conventional farmers. The suppliers face economic and regulatory challenges. The representatives from the civil society were divided in their response to BFPs. While the national representatives were enthusiastic about that BFPs can solve environmental problems, the regional representatives underlined that BFPs could legitimize intensive livestock production that is decoupled from land resources.

To summarize, the critical limiting factors for production and adoption of BFPs include lack of knowledge among farmers, regulatory and economic barriers, product properties as well as worries about long term effect and further intensification of livestock production. Critical enabling factors include farmers' appreciation for organic matter and trust in safety assessments by the authorities. Improved communication between farmers, producer and the civil society could be important to secure BFPs that will be used by farmers and that contribute to a sustainable future. Finally, it is important to emphasize that policy instruments will be needed to increase the adoption of PFPs and that BFPs' effects on agricultural intensification could be important to consider when formulating these polices.

## Author contributions

VK, BF, and OH designed the study. Interviews was carried out and analyzed by HH, BF, and VK. VK was the main responsible for writing the article, with important input from BF (especially chapters 2.2, 3.1, and 3.3), HH (especially chapters 2.2 and 3.2), OH (especially chapter 1), and EB (especially chapter 2.1). All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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