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Expert insights from industry informants

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Exploring economic feasibility of marine-based organic fertilizers: Expert insights from industry informants

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Abstract: Worldwide, fisheries and related industries produce large quantities of marine residues, such as fish cutoffs, heads and backbones, often ending up as waste or only extracting the fish oil and soluble protein via hydrolysis, leaving sediment of bone particles, etc. unused. However, research and practice show that these residues can be applied as fertilizers with an immediate effect on plant growth. If production of fertilizers is economically viable, utilization of marine residues can be improved and simultaneously meet a demand for fertilizers in certified organic farming. This paper analyzes economic viability of producing marine-based organic fertilizers in Norway and Denmark. From interviews with fertilizer producers, the willingness to pay for one kilogram of an acid preserved bone material of captured white fish, made from minced heads, backbones, skin, organs etc., appearing as a residue product when extracting fish oil and soluble proteins during hydrolysis, was identified. With an average N-content of 4.2%, a positive willingness to pay was identified, between 0.078 and 0.272 €/kg, dependent on market conditions. With the positive willingness to pay, it may be economically viable to apply the material to produce marine-based organic fertilizers, revealing a potential for further exploitation of the by-products from captured white fish for fertilizers in certified organic farming.

Keywords: Marine residue, White fish marine residues, Willingness to pay, Economic viability.

1. Introduction

As global food systems struggle to meet the demand from a growing population, the pressure on marine resources and agriculture intensifies (Penuelas et al., 2023). This challenges the concept of a traditional linear production model in food production that generates significant organic waste streams, which potentially undermines environmental, climate, and economic sustainability of the sector. The circular bioeconomy model offers a transformative approach, applying organic waste as a resource for closing nutrient gaps and simultaneously reducing ecological footprints. This study elicits industry insider information on the emerging market of using marine residues for producing organic fertilizers and identifies economic opportunities and barriers.

Globally, marine fisheries and fish processing industries generate millions of tons of residue products annually, much of which remain underutilized or discarded, contributing to pollution and greenhouse gas emissions (Food and Agricultural Organization of the United Nations, 2024). By-products of fish processing for human consumption can represent up to 70% of the whole fish, varying with species and product form (Food and Agricultural Organization of the United Nations, 2025). In well-organized and efficient value chains, these by-products are used for pet food production, fish meal and fish oil production, and bioenergy generation. Yet, after processing fish residues for feed, a significant amount of material remains available, rich in valuable nutrients (nitrogen, phosphorus, and calcium), but hardly digestible for farmed animals (including raised fish) due to its high mineral content. Further, considerable amounts of fish by-products are still not utilized at all but instead discarded. Together, these materials represent an untapped potential for improved resource efficiency and value creation in the marine sector.

Over the past decade, the value of biological by-products has increased markedly across both the agricultural and marine sector. Historically, many residues carried zero or negative value, and biogas plants were often paid to accept slaughterhouse waste or fish residues. As new and more valuable utilization pathways have emerged, competition for these materials has intensified and by-product prices have risen. Evidence from the Danish biogas sector illustrates this broader trend. Jacobsen et al. (2013) reports that biogas producers have shifted from receiving gate fees for waste inputs to paying for many of these substrates, which reflects their rising value in alternative markets. This development shows a general historical shift in which residues from agriculture, aquaculture, and fisheries are increasingly regarded as valuable resources rather than waste.

Fish residues (heads, bones, skin, and viscera) contain nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca), alongside other essential plant macro- and micro-nutrients, and can be transformed (e.g. via composts, hydrolysates, silage) into fertilizer products with agronomic value (Zhang et al., 2023). Using hydrolyzation, oil and solubilized proteins may be utilized for food or feed, while heavier particles can be used as fertilizer, which is approved in certified organic farming in Norway and Denmark (Danish Agri-Food Agency 2024; Norwegian Food Safety Authority 2025). Using fish as fertilizer is not a new concept, as fish by-products have been used as a soil amendment in coastal regions for centuries (Ahuja et al., 2020).

In certified organic farming, synthetic nitrogen fertilizers are not allowed, and mineral fertilizers are only permitted under certain conditions after justification of a demand (European Commission 2018). As a result, organic farmers primarily rely on manure and other organic materials, including commercial fertilizers produced from meat- and bone meal, blood, horns, feathers, and plant residues derived from conventional farming. However, using fertilizers produced with manure and residues from conventional farming threatens the integrity of certified organic farming. Recycling of nutrients and organic matter is well in line with the basic organic principles (IFOAM Organics International 2020, European Commission 2018), and harvesting of natural materials is an integrated part of organic farming. Hence, organic farming may increasingly demand fertilizers derived from recycled materials from other sectors than conventional agriculture. In that respect, captured fish are a relevant option commonly applied for fertilizers in certified organic farming in the US, but to a lesser extent in Europe (Ahuja et al. 2020).

The transformation from a linear to a circular bioeconomy may not materialize without proper incentives or without addressing regulative constraints (Sørensen, 2018). To this end, the EU Farm to Fork strategy aims to increase the share of organic farmland from the current 10% to 25% in 2030 (European Commission 2020) to improve environmental sustainability. This is expected to increase the demand for organic fertilizers permitted in organic farming. Hence, an increasing demand for fertilizers made from recycled organic materials is to be expected in the near future.

The purpose of this paper is to identify the economic viability of using residues from white fish to produce organic fertilizers in Norway and Denmark. To narrow the scope of the analysis, the willingness to pay is identified only for acid-preserved, bone-rich residue materials (heads, backbones, etc.) of captured white fish (including cod Gadus Morhua, haddock Melanogrammus aeglefinus, and saithe Pollachius Virens). Residues from pelagic fish species like herring and mackerel are usually rich in fat and contain much less bony material, but they are almost fully utilized for feed products in the two countries, while white fish residues could still be more intensively utilized. The study covers Norway and Denmark because these countries have a high demand for organic food products (Trávnicek et al. 2025), an established organic fertilizer industry, and significant industry for captured fish. Economic viability was identified by asking existent producers of organic fertilizers for their willingness to pay for hydrolysate residue material of white fish.

A high potential of white fish residues as fertilizers for crop plants was demonstrated by Løes et al. (2022). Bone-rich white fish residues were shown to have a rapid effect on plant growth, indicating that the N is readily available for plant uptake. To supply crop plants with K, another marine material may be applied: brown macroalgae, which has a much slower, yet longer lasting effect on plant growth. In the Norwegian study (Løes et al 2022), fertilizing materials were applied in the year of ley establishment (2019) at a rate of 160 kg N per hectare. It showed that a combined fertilizer, where 70% of total N was derived from bone-rich fish material and 30% from seaweed, achieved the highest yield performance of grass-clover ley over a 3-year period. The accumulated grass dry matter production during 2020-2022 was 13.6 tons per ha for the non-fertilized baseline, 17.4 tons (+28%) for a commercial organic fertilizer made by a mix of dried poultry manure and meat and bone meal, 17.6 tons (+29%) for bone-rich fish material, 21.3 tons (+57%) for seaweed residues, and 22.6 tons (66% yield increase) for the combined fishbone and seaweed fertilizer. A positive effect of bone-rich white fish residues was also found by Molosag et al. (2023), in strawberries grown in a greenhouse. Hence, marine-based fertilizers, particularly those combining fish and algae materials, have demonstrated higher yield responses than comparable organic fertilizers.

The willingness to pay for bio-based fertilizers was estimated in a choice experiment finding that certified organic farmers in seven European countries prefer concentrated bio-based fertilizers. They were willing to pay 65% of the price of the traditional mineral fertilizer, provided that it was homogenized and solid, and that the N-content is certain (Tur-Cardona et al. 2018). Furthermore, Hills et al. (2020) find that farmers in Washington State prefer pelletized over wet forms and are willing to pay 39% more for the pellets assuming the same N-content per kg, while Moshkin et al. (2023) found that bio-based fertilizers sold at 54-70% of the price of mineral fertilizer would maximize the market share of bio-based fertilizers. A study of optimized utilization of fish industry residues in the Western Pacific (Dominy et al. 2014) showed that utilization as a liquid fertilizer at a price of 3.50 USD per gallon (ca. 0.92 USD per liter) gave the best profit, compared with fish silage, fish meal, or fish oil production. Theden-Schow et al. (2026) showed that certified organic farmers in Denmark are willing to pay a price premium for organic fertilizers in solid over liquid forms and that plant-based inputs are valued higher than marine- and animal-based inputs. This paper contributes by analyzing the economic viability of using residue materials of fish for producing fertilizer applicable in certified organic farming.

2. Background

2.1 The Value Chain of White Fish Residues

Considerable amounts of fish residue products are available in both Norway and Denmark. While residues from pelagic fish are almost entirely utilized in the two countries (Ahuja et al., 2020; Myhre et al., 2023; Tveteraas et al., submitted), residues from white fish species (e.g. cod, haddock, saithe) from the fishery sector are still partly underutilized. Ahuja et al. (2020) reported that, in Norway, their utilization rate has increased from 40% in 2012 to 60% in 2018. They further estimated the total volume of available white fish residues at 120,000 tons in 2018, while Tveteraas et al. (submitted) calculated this amount to be approximately 100,000 tons in 2023. Thus, while the utilization of white fish residue products from the Norwegian fishery sector appears to be increasing, significant volumes remain underutilized.

In Denmark, smaller quantities of fish are landed and processed, and consequently smaller quantities of residue products are generated. Data availability on residue products and utilization rates is considerably lower in Denmark than in Norway, where annual reports on the seafood industry are publicly available. Tveteraas et al. (submitted) estimated the volume of residue products from white fish and aquaculture in Denmark at 50,000 tons in 2023, although they conclude that most of these by-products are already being used in other industries.

These numbers together lead to two implications: (i) significant quantities of residue materials from the white fish sector remain currently underutilized, especially in Norway, and (ii) the exact quantities of these raw materials are difficult to determine, given the complexity of the sectors in the two countries and the limited data availability.

In both countries, the value chains for marine residue products have significantly changed in recent years. Prior to the Covid-19 pandemic, both Norway and Denmark had a substantial fur industry, which utilized white fish residues for feed. However, this industry was shut down in both countries, in Denmark explained by governmental assessments that fur animals posed a potential risk for transmitting Covid-19 to humans (Danish Ministry of Food, Agriculture and Fisheries 2020) and in Norway by animal welfare reasons (Norwegian Ministry of Agriculture and Food 2020). This closure released substantial amounts of fish residues which had previously been utilized in the fur industry. Given fur animals' unique ability to digest bone-rich material, the residue products could not simply be redirected for use as feed for other animals and therefore required alternative utilization routes.

Following these changes, a large proportion of fish residues in Norway is now processed through liquefaction and stabilization methods designed to preserve the otherwise highly perishable residue material. These processes are often referred to collectively as fish silage or fish hydrolysate production (Ahuja et al., 2020). Domínguez et al. (2024) reported that in 2014, approximately 41% of all fish by-products generated in Norway were processed in this way. In the Norwegian fisheries sector, the process typically involves maceration and acid hydrolyzation, in which acid is added to the raw material, leading to enzymatic liquefaction and separation at low pH into a liquid protein phase, an oil phase, and a sediment fraction (Myhre et al., 2023). While the former two fractions are further valorized for the production of feed products, the latter sediment fraction is an acid-preserved, bone-rich material with high ash content that is typically unfit for feed production and is currently either discarded or redirected for the use in bioenergy generation. However, its high bone content provides the material with significant amounts of nitrogen, phosphorus, and calcium, making it suitable for further processing into fertilizer products (Ahuja et al., 2020; Løes et al 2022).

In Denmark, the production of fish silage is far less common. The utilization of white fish by-products reflects differences in raw material quality and market demand. High-quality by-products are processed for human consumption or pharmaceutical production, where prices are highest. By-products of slightly lower quality are sold to the pet food industry, while the vast majority of residue materials are utilized in fish meal and fish oil factories. This industry is highly technologically developed and therefore leaves minimal to no residues after processing. Low-quality residues and mortalities from aquaculture, which have little to no market value, are used for biogas. Thus, only minimal quantities of fish residues remain available for fertilizer production in Denmark.

In this paper, the willingness to pay from companies producing organic and mineral-organic fertilizers in Denmark and Norway is elicited for the acid-preserved, bone-rich residue material described above.

2.2 Economics of Fertilizer Production in Denmark and Norway

To assess whether the use of marine residues is economically feasible in practice, it is useful to understand the financial performance of the companies that could utilize these materials. The following section therefore presents key economic figures for fertilizer producers in Denmark and Norway, providing context for their potential capacity to adopt new input materials. In the two countries, four companies were producing fertilizers permitted to be applied in certified organic farming during 2017-2023. These appear in Table 1 anonymized to company A-D.

Table 1. Key Economic Numbers for Organic Fertilizer Producers in Denmark and Norway, 2017-2023[1].

	2017	2018	2019	2020	2021	2022	2023
Company A							
Net turnover (€ million)	118,045	119,183	113,545	126,816	136,987	158,880	90,453
EBIT[2] (€ million)	11,507	13,455	22,461	24,695	19,128	751	-9,404
Rate of return (% assets)	11.6	13.0	23.0	26.2	21.0	0.8	-13.6
Value added[3] (€ million)	25,282	29,357	31,044	42,712	38,361	19,003	4228
Total assets (€ million)	98,986	103,668	97,770	94,299	91,010	90,376	69,162
Company B							
Net Turnover (€ million)	.	.	.	.	.	.	.
EBIT[2] (€ million)	321	640	490	797	628	609	677
Rate of return (% assets)	9.4	17.7	11.4	17.1	12.8	9.6	7.3
Value added[3] (€ million)	1,324	1,584	1,415	1,859	1,897	1,925	2,287
Total assets (€ million)	3,414	3,620	4,289	4,655	4,891	6,326	9,274
Company C							
Net Turnover (€ million)	1,811	1,872	2,009	2,097	2,773	5,319	3,600
EBIT[2] (€ million)	189	215	153	65	208	595	28
Rate of return (% assets)	11.7	12.6	8.5	3.2	8.3	17.3	0.9
Value added[3] (€ million)	302	533	539	532	672	1,151	623
Total assets (€ million)	1,619	1,701	1,797	2,037	2,501	3,432	3,132
Company D							
Net Turnover (€ million)	1,680	1,631	1,933	1,831	2,795	2,926	1,967
EBIT[2] (€ million)	-34	-117	-205	-253	65	-95	-649
Rate of return (% assets)	-1.2	-4.4	-7.2	-9.4	2.3	-2.8	-20.3
Value added[3] (€ million)	442	443	331	311	761	641	15
Total assets (€ million)	2,747	2,689	2,855	2,682	2,806	3,366	3,200
Total							
Net Turnover (€ million)	.	.	.	.	.	.	.
EBIT[2] (€ million)	11,983	14,192	22,899	25,303	20,029	1,859	-9,347
Rate of return (% assets)	11.2	12.7	21.5	24.4	19.8	18.0	-11.0
Value added[3] (€ million)	27,350	31,918	33,329	45,415	41,691	22,719	7,153
Total assets (€ million)	106,767	111,678	106,710	103,673	101,208	103,501	84,768

Notes:

1. Over the period, five companies produced organic fertilizers in the two countries; However, annual accounts were available for only four of them.
2. Earnings before interest and taxes.
3. Value added is a measure of the contribution of the companies to the national economy (Gross Value Added), calculated as turnover minus operating costs, excluding salary costs, depreciations and financial net costs.

Source: Company financial data retrieved from Proff.dk (Denmark) and Proff.no (Norway), accessed in August 2025.

Of the four companies displayed in Table 1, two are Danish and two Norwegian. The largest company, company A, accounts for 92% of the total assets of the four companies and has a broad range of activities, including the production of organic fertilizers, livestock feed, waste management, rendering and recycling. Company B-D specializes in the production of organic and organo-mineral fertilizers.

The totals indicate high rates of return on total assets, above 10% during 2017-2021, and still positive in 2022 (18%). In 2023, however, the deficits were large, with a rate of return on total assets of -11%. Given that company A was involved in activities beyond the production of organic fertilizers, the aggregated totals may be somewhat misleading. Nevertheless, the three specialized companies exhibit the same pattern of declining rate of return. Hence, during 2017-2021, companies generated substantial surpluses. In 2023, deficits were observed, mainly due to price increases on energy following the Ukraine war.

3. Methodology

The economic viability of using marine residues for producing organic fertilizers is assessed for companies already engaged in organic fertilizer production. It is evaluated through a hypothetical choice framework in which companies are asked to state their willingness to pay (WTP) for an acid-preserved bone-rich material derived from captured white fish residues. The average WTP for one unit of this residue material of white fish must be positive for production to become economically viable, as alternative uses, waste disposal or bioenergy generation, provide little to no economic return. In some cases, companies even pay a gate fee to dispose of the material, resulting in a negative alternative value corresponding to the size of the fee.

WTP is applied instead of identifying all extra cost and income items associated with the new activity. This approach is chosen due to the uncertainty involved in identifying individual items, stemming from the heterogeneity of production systems among the companies involved. By asking companies to state their WTP, it is not necessary to identify all items separately. Instead, the companies state their best estimate of the WTP at which they would start using by-product materials of white fish, considering the economics of their company.

The number of organic fertilizer-producing companies in Norway and Denmark is limited, with six firms identified as potential users of marine-based raw materials (two in Norway and four in Denmark). The sampling technique followed a purposive, non-probabilistic design, in which all organic fertilizer companies in the two countries were identified and contacted. This sampling method is appropriate in exploratory or pilot WTP-studies, where the target population is small and well-defined (Bateman et al. 2002). One company operated solely as a wholesaler rather than a producer, leaving a target population of five producers. With one company declining participation, the sample consisted of the remaining four companies, which agreed to be interviewed for this research project. This results in an 80% response rate, and thus high coverage of the target population. While the small sample implies that the results are less generalizable and more uncertain than those from larger samples, the high response rate strengthens the contextual representativeness of the findings and provides reliable insights based on the knowledge of key personnel regarding the economics of their companies.

Interviews were conducted via video calls where possible (n=2), and via phone calls when technical issues prevented online participation (n=2). Each interview gathered detailed information about production practices, input materials, and perceptions of marine-based fertilizer products, and lasted between 25 and 40 minutes.

Small-sample WTP studies typically rest on several assumptions. First, that the target population is relatively homogeneous with respect to the behavior studied (so that each respondent provides substantial information about group tendencies), and that the purpose is to generate indicative or exploratory insights rather than statistically generalizable estimates. Such studies assume that qualitative information can partially compensate for the lack of statistical power.

The approach also carries clear limitations, notably reduced precision, limited scope for statistical inference, and sensitivity to outliers or respondent-specific biases. Accordingly, the WTP estimates must be viewed as indicative measures of market potential among existing producers, suitable for feasibility assessment of an extra activity of existing companies rather than for formal economic valuation at the industry level.

Let v denote economic viability, WTP the willingness to pay for one unit of the acid preserved bone-rich residue material of captured white fish and AP the unit price of the fish material in alternative use. Equation (1) expresses the condition for the additional activity to be economically viable.

$$v = WTP - AP > 0 \quad (1)$$

If $v > 0$ then it is economically viable to start the new product line, while it is not if $v < 0$. Equation 1 only reflects the minimum condition for economic viability. A positive value implies that the fertilizer company could pay for the material and still expect a profit from the additional activity. Transport costs are disregarded by this criterion, as they are assumed to be taken into consideration when companies state their WTP. Since there is no current use of the material, the unit price in alternative use $AP = 0$. In cases with no alternative use where fish processing companies must pay a gate fee (f) for getting rid of the material, economic viability claims that: $v = WTP - f > 0$.

Stated preferences methods were applied to identify the WTP for the hypothetical additional activity of the companies. Each interview provided a detailed description of the fertilizer product characteristics in order to ensure that responses were as consistent as possible. Given the small sample size, value and standard deviation of WTP per unit of marine residues were the only statistics to be computed.

The WTP statements refer to an additional activity for companies already producing a similar product based on other raw materials. Hence, we assume that no further technological investments would have to be made to process white fish residue materials into organic fertilizers.

3.1 Data Collection

All five companies producing organic fertilizer in Norway and Denmark were contacted and four agreed to participate in interviews held between August and September 2024. The interviews were structured into three parts. (1) Respondents first described their production process and answered five questions concerning their use of raw materials. (2) They were then asked to state their WTP for one kilogram of a specified marine residue material. (3) Finally, the interviews ended with further qualitative questions concerning the use of raw materials and the relative importance of the quantity, quality, availability, and price of the raw material for their purchasing decision.

Before stating their WTP in part (2), they were informed that:

> "The product contains acid preserved fish bone material and is likely going to be composed of residues from captured white fish (cod, saithe, etc.) and contain heads, backbones, skin, organs, etc. The material may be ground and conserved with preservation to pH < 4 e.g. by formic acid. During storage, the material will hydrolyze and split into a top layer of oil, followed by hydrolyzed proteins and a bottom layer of sediments. The sediment has a large proportion of fish bone, and contains significant amounts of calcium and phosphorus, but is also rich in proteins such as collagen, and hence has a very rapid growth effect due to easily available nitrogen. The formic acid may emit carbon monoxide and is corrosive. The average nutrient values as % of dry matter are: Nitrogen 4.23%, Phosphorus 10.3%, Potassium 0.11%, Calcium 13.9% and Magnesium 0.1%."

Further, it was mentioned that "depending on the storage and processing techniques, the nitrogen levels of the material vary significantly and was found to be up to 15% of dry material in some cases."

WTP was elicited under two hypothetical scenarios that differed in the nitrogen content of the residue material. The scenarios were the following:

(1) Assuming the average N-content (4.23%) of fish silage residues.

(2) Assuming the maximum N-content (15%) observed in fish silage residues.

WTP was elicited using a payment card format (Bateman et al. 2002). Respondents were presented with a predefined list of price options ranging from 0 to 0.33 €/kg in increments of 0.03 €/kg and asked to select the maximum amount they would be willing to pay for one kilogram of the material under each scenario. They could provide another value if none of the predefined amounts reflected their preferences.

Interviews were followed by a focus group discussion in October 2024, to which all interview participants were invited. Representatives from three companies participated and were asked to state their opinions on the following three pre-announced qualitative questions:

i. What are the current limitations (economic, technological, available marine residues, etc.) you see in entering a new product line that uses marine residues for organic fertilizer?
ii. Is there a need for a third party between seafood suppliers and organic fertilizer producers (e.g., handling logistics and/or processing) to facilitate the establishment of a new value chain for marine residues to organic fertilizer?
iii. What role does regulation play at any stage in supporting or hindering this value chain?

During the focus group discussion, participants were also asked to clarify details from the initial interviews.

4. Results

The first part of the interviews revealed that the production process in this industry begins with the sourcing of raw materials from the rendering, slaughtering, and crop processing industry. Slaughterhouse by-products, such as blood, feathers, and carcasses of dead livestock are processed into meat and bone meal. Poultry manure and semi-solid digestates are further animal-based inputs, while legume seeds, and residues from the sugar, potato, and other plant-processing industries are common plant-based sources of nutrients. In the fertilizer factories, the raw materials with a dry matter content of >85% are blended according to formulated recipes to meet the nutrient requirements of various crops, made into pellets, and packed for distribution.

In the second part of the interview, each company stated their WTP for one kilogram of by-product materials of white fish under the two hypothetical scenarios. Since only two companies provided WTP values for scenario 2, the WTP for the remaining two companies in this scenario was estimated by applying the same percentage increase in WTP observed among the companies that responded to both scenarios. An additional third scenario was later calculated based on scenario (1) by adjusting the WTP with a factor of 3.5 to reflect the organic fertilizer price levels in 2022, which were 3.5 times higher than in 2024. The final results are presented in Table 2.

Table 2. WTP for 1 kg of By-Product Material of White Fish Stated by Organic Fertilizer Producers.

Scenarios	€/kg.[1]
1. Average N-content and low organic fertilizer prices	0.078 (0.074)
2. Maximum N-content and low organic fertilizer prices	0.311 (0.256)
3. Average N-content and high organic fertilizer prices	0.272 (0.293)
Number of companies	4

Note: 1. Standard deviation in parenthesis.

The results in Table 2 indicate that organic fertilizer producers, under the market conditions of 2024, are on average willing to pay 0.078 €/kg for by-product materials of white fish containing 4.23% N (scenario 1). In cases where the N-content can be increased to 15%, the estimated WTP rises to 0.311 €/kg (scenario 2), although this estimate is based on responses from only two companies. Under the favorable market conditions in 2022, when the prices of organic fertilizers were 3.5 times higher than in 2024, the hypothetical WTP is assumed to scale proportionally, yielding an estimated value of 0.272 €/kg (scenario 3).

Respondents were not specifically instructed whether transport costs should be included in their stated WTP. Yet, because buyers in this industry typically evaluate raw materials in terms of their cost per kilogram, we interpret the stated WTP as the maximum delivery price the producers are willing to pay.

Building on this interpretation, the economic viability requires that the transport costs do not exceed the stated WTP. In Denmark, transport costs for comparable residue materials are approximately 0.07 €/kg for domestic deliveries (personal communications with industry informants), implying that the stated WTP in scenario 1 would be sufficient to cover domestic transport costs. However, the raw material is only available at scale in Norway, as discussed in Section 2, and respondents were not informed about the geographic source of the raw material. Hence, the international transport costs are expected to match or exceed 0.078 €/kg, rendering this scenario economically unviable for Danish fertilizer producers. Scenarios (2) and (3) are likely economically viable for the Danish case, considering the magnitude of WTP difference to scenario (1), although some uncertainty remains.

In Norway, where the residue material is produced domestically, long domestic transport distances may still challenge economic feasibility if the delivered costs exceed the stated WTP. Under the delivered-price interpretation, viability is most plausible when sourcing residues from proximate processors whose transport costs remain within the relevant WTP levels.

Overall, this interpretation suggests that scenario (1) is unlikely to be viable in Denmark, whereas scenarios (2) and (3) are likely viable in both countries, but remain uncertain pending more precise information on transport costs. This outcome reflects the fact that the material's current alternative uses, which are either waste disposal or bioenergy generation, provide no economic return, and in some cases even entail disposal costs.

The third part of the interviews contained qualitative questions on the use, quality, and availability of raw materials. The results of these questions are presented in Table 3.

Table 3. Interview Results on Raw Material Use in Organic Fertilizer Production.

Question	Answers
1. Number of companies interviewed	4
2. What sources of raw materials are you using for your organic fertilizer production?	Plant residues. Plants like horse beans and peas. Dead animals. Meat and bone meal. Chicken manure.
3. In what form do you typically receive the raw materials	Solid (wet or dried). Whole dead livestock, such as pigs and calves.
4. Are there specific requirements related to the form of raw material	Requirements on collection, transport, disposal and traceability.
5. Are there any quality requirements, apart from preparation and form, that the raw materials need to meet?	Raw material must have a certain NPK content. They may not contain any weed seeds, lumps or stones.
6. What are your concerns about using marine residues as a raw material in your organic fertilizer production?	Raw materials must not contain PFAS, heavy metals, or salt. The price must not be too high.
7. How important is the quantity of available raw material for your likelihood of purchase?	5.0
8. How important is the fluctuation of quality parameters of the raw material for your likelihood of purchase?	4.7
9. How important is the consistency of availability of the raw material (seasonality) for your likelihood of purchase?	4.0
10. How do you rank the relative importance of quantity, quality, availability, and price of the raw material in your decision-making process? (1 = most important)	Price (mean rank 1.3), quality (2.3), quantity (2.7) and availability (3.7).

Note: Questions 7–9 were answered on a five-point Likert scale ranging from Very important (5) to Very unimportant (1). The values reported are mean scores across all respondents.

The results show that the interviewed producers currently rely on plants (e.g. peas and horse beans), plant residues, chicken manure, dead livestock and meat and bonemeal as raw materials. The handling of these raw materials must comply with regulations on collection, transport, disposal and traceability to ensure the safe and sustainable treatment of animal by-products (European Commission 2009). Furthermore, the raw materials must be free of weed seeds, lumps and stones and must contain a certain NPK content.

The main concerns expressed by the companies in both countries related to the potential presence of PFAS[1], salt, and heavy metals in marine residues. PFAS contamination was considered to be the most critical issue, as marine by-products were believed to contain high levels of these substances, for which a strict zero-tolerance policy is enforced in organic farming. The Danish companies were particularly concerned about the presence of PFAS in marine residue materials, which they underscored in both the interviews and in the subsequent focus group discussion. One company explained that "in applying marine residues, it would be very difficult to comply with the zero-tolerance claims for PFAS in fertilizers to certified organic farming". The strong focus of the public debate on the poor ecological state of the Baltic Sea and the presence of PFAS in it may explain this concern among Danish fertilizer producers. Interviewees in both countries emphasized that the lack of control over the composition of marine raw materials poses a concern. Continuous testing of marine residues was seen as a necessary measure, which may increase costs to a level that would make production economically unviable.

A sufficient supply of raw materials was identified as highly important (mean score 5.0) in respondents' decision-making process. Quality (4.7) and consistency in supply of marine residues (4.0) were also seen as important factors. In fact, all three factors appear to be relevant for the companies' consideration of whether or not to engage in this novel activity. The focus on a sufficient supply reflects the fact that companies do not currently use marine residues and therefore require access to reasonable quantities of raw materials to achieve a positive net return on the new activity. The finding that year-round consistency in supply is somewhat less important than overall supply (4.0 vs. 5.0), may indicate that existing production lines could accommodate marine residues even if their availability is subject to seasonal fluctuations. In addition, when asked to rank the

[1] PFAS is the abbreviation for per- and polyfluoroalkyl substances, a group of chemicals widely used for their water resistance properties. PFAS enter the marine environment primarily through wastewater discharges and accumulate in aquatic organisms, including fish, through ingestion of contaminated particles.

relative importance of price, quality, quantity, and consistency, producers placed price as the most important factor, followed by quality, quantity, and consistency. This highlights that economic considerations remain central, even when supply-related factors are rated highly.

Lastly, a focus group discussion was conducted to confirm and elaborate on the findings from the interviews regarding limitations to using marine residues in certified organic fertilizer production and the role of regulation. Participants largely reiterated their concerns about PFAS, heavy metals, and salt, emphasizing the challenges posed by the zero-tolerance policy for PFAS in organic fertilizer production. Danish producers also restated their reservations about using wild-caught fish, noting that fish from uncontrolled marine environments are considered unsuitable for certified organic farming.

While Norwegian producers focused primarily on economic viability, Danish producers emphasized both economic viability and compliance with zero-tolerance rules for PFAS and heavy metals in raw materials. Table 4 summarizes the results, showing that economic viability is not the only barrier for using fish residues in organic fertilizers. Given the uncertainty of future prices of marine residue materials, the barriers and implied risk factors listed in Table 4 are also relevant decision variables.

Table 4. Perceived Barriers to the Use of Marine Residues in Organic Fertilizer Production, as Reported by Producers in Norway (NO) and Denmark (DK).

Barrier Type	NO Companies	DK Companies
Economic viability (price)	Medium	Medium
PFAS/contamination	Medium	Critical
Supply volume	Critical	Medium
Supply consistency	High	High
Regulatory clarity	Medium	Medium

Note: Barrier levels (Medium, High, Critical) reflect their relative importance. 'Critical' indicates the most significant or binding constraint 'High' denotes a major but potentially manageable barrier, and 'Medium' represents a moderate concern mentioned by fertilizer producers.

5. Discussion and Conclusion

The shift from a linear production model toward a circular bioeconomy relies on identifying viable pathways for recycling biological residues into valuable products. This study contributes to this path by assessing whether underutilized white fish residues can be integrated into organic fertilizer production in Denmark and Norway in an economically feasible manner.

The results indicate that the economic viability of using acid-preserved fish bone material resulting from hydrolysis depends strongly on the products' nutrient content and the prevailing market conditions. In the case of an average N-content of 4.23% of dry matter and organic fertilizer price levels of 2024 (scenario 1), the stated WTP from Danish producers was just high enough to cover domestic transport costs. However, since the raw material is only available at scale in its assumed form in Norway, international transport costs are likely to exceed the stated WTP from Danish producers under this scenario. By contrast, scenarios (2) and (3), reflecting higher nutrient concentrations (scenario 2) or more favorable fertilizer market conditions (scenario 3), indicate a greater economic potential, but the feasibility remains contingent on the ability to manage transport costs within the stated delivered-price ceilings.

In Norway, where the residues are available domestically, the economic outcome depends less on cross-border logistics and more on the proximity between fisheries and fertilizer producers. Taken together, the results suggest that the establishment of a circular value chain for marine residues in fertilizer production is governed by a combination of factors: the nutritional content of the raw material, the prevailing market prices for organic fertilizers, and practical considerations such as transport and transaction costs. Under current market conditions, and assuming average nutrient contents of white fish silage residues, the establishment of a novel value chain for marine-based fertilizers appears unlikely to be viable in Denmark, whereas localized sourcing in Norway remains more promising. Although parts of Southern Norway lie geographically closer to North-Western Denmark than to Northern Norway where much of the fish processing industry is located, the costs associated with international transport are still assumed to represent a substantial barrier.

Additional constraints to using fish residues for organic fertilizer production include according to some responses the potential presence of PFAS and heavy metals, which accumulate in wild fish through the food chain. In certified organic farming, zero tolerance for these substances are mentioned. While it is technically possible to remove them, it is costly. Therefore, continuous testing to minimize the risk of contaminants is necessary when applying marine residues, which further adds costs. From the perspective of organic fertilizer producers, marine residues are a potential new source of raw materials in a market where the EU's Farm to Fork strategy seeks to expand certified organic farming (European Commission 2020). However, the economic viability remains challenged by the perceived lack of control over contaminant accumulation within marine ecosystems.

Access to sufficient raw material of consistent quality is another major barrier. Although large volumes of underutilized residues appear to exist in Norway, limitations in freezing and processing capacity at sea, combined with weak incentives to bring residues ashore, may result in some by-products being discarded at sea (Strand et al. 2024). Tveteraas et al. (submitted) further showed that the potential volume of fish residues available for organic fertilizer production has been decreasing over the past decade, as utilization for higher value purposes has increased.

While this study specifically focused on the economic viability of acid-preserved residues from wild-caught white fish, other opportunities exist for utilizing different forms of marine residues. These include manure from farmed organic fish, in particular salmon and trout, by-products from conventionally farmed fish species, and algae. The advantage of applying residues from organic fish farms is that certified and documented organic value chains already exist. However, sludge from farmed fish is currently not approved for certified organic farming in the two countries. In addition, the supply of such residues is limited due to the small scale of organic aquaculture production in the two countries, and handling the sludge is costly, given its high content of water.

Economic viability ultimately depends on market conditions. Potential markets for marine-based fertilizers extend beyond just certified organic farming. One company noted: “We have inquiries from conventional farmers asking for organic fertilizers to improve the soil nutrition for longer than one year,” and further added that “demand for organic fertilizers from municipals is also increasing.” Hence, potential markets include certified organic and conventional farming, private households, and the public sector. Certified organic farming presents a large market potential in the EU, while conventional farming forms an even larger potential market, albeit at lower prices, since marine-based organic fertilizers would have to compete with mineral fertilizers on this market. While mineral fertilizers often target the nutritional needs of plants and soils more precisely than organic fertilizers, the latter have demonstrated a positive long-term effect on soil quality that could gain them a competitive advantage. Moreover, private households and the public sector may be willing to pay higher prices for more sustainable products. The WTP among private buyers is likely going to be higher than in the farming sector, as quantities purchased are smaller and individual preferences for environmental properties vary more widely. By contrast, farmers’ WTP is more directly linked to farm earnings.

For fertilizer producers, the demonstrated economic viability of using acid-preserved bone material provides an incentive to develop new production lines. In Norway, large quantities of the residue material are available, but long transport distances may pose a challenge. In Denmark, the main constraint is domestic availability of the acid-preserved bone material. However, since residues could be imported from Norway, transportation costs again become the main limiting factor.

The results should be interpreted with caution, as the WTP estimates are based on a small sample. While this limits the generalizability and increases the uncertainty of the findings, the responses nonetheless provide valuable insights from key industry stakeholders. Moreover, the analysis focused on economics and did not account for potential socio-economic benefits of replacing mineral fertilizers with organic alternatives. Future research may therefore focus on assessing the broader societal value of such substitution and its potential to reduce nutrient losses and greenhouse gas emissions over time and across regions.

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