TOWARDS A CIRCULAR PHOSPHORUS ECONOMY IN NORWAY

STRATEGIES FOR INTEGRATING AGRICULTURE AND AQUACULTURE SECTORS AT MULTIPLE SCALES

NIBIO NORWEGIAN INSTITUTE OF BIOECONOMY RESEARCH

MINDP

NTNU Norwegian University of Science and Technology

AKNOWLEDGEMENTS

PROJECT FUNDERS

Funded by
The Research
Council of Norway

REPORT AUTHORS

Daniel Beat Müller, NTNU
Miguel Las Heras Hernández, NTNU / NILU
Avijit Pandit, NTNU
Anne Falk Øgaard, NIBIO
Kjell Inge Reitan, NTNU

PROJECT TEAM

NTNU Industrial Ecology

Daniel Beat Müller
Miguel Las Heras Hernández
Avijit Pandit
Nils Dittrich
Francis Barre
Anna Eide Lunde
Loïs Lozach
Thomas Galea
Helen Ann Hamilton
Simona Sharma

NTNU Biology

Kjell Inge Reitan
Ingeborg Hollekim Bringslid
Inka Anglade

NIBIO

Anne Falk Øgaard
Eva Brod
Ola Hanserud

DTU

Jens Kjerulf Petersen

ADVISORY PANEL

Andrea Viken Strand, SINTEF
Anna-Sara Bergeland, Norwegian Environmental Agency
Anne Katrina Berg, Norsk Landbruks Rådgiving (NLR)
Arne Haarr, Norsk Vann
Asbjørn Veidal, Landbruksdirektoratet
Benjamin Kleppe, Bellona
Ellinor Bævre Heggset, Trøndelag County Council
Emil Beddari, Framtiden i våre hender
Erik Hagen, Norwegian Western Sahara Resource Watch
Gisle Berge, Statistics Norway
Hanne Digre, SCALE AQ
Harald Steffensen, Skretting
Helen Ann Hamilton, Biomar
Jens Måge, Avfall Norge
Jon Svenningsen, Jordpro
Julia Fossberg Buhaug, Lerøy Midt
Karen Johanne Baalsrud, Norwegian Food Safety Authority
Kari Marte Sjøvik, Norges Bondelag
Kine Martinsen, Norwegian Environmental Agency
Knut Vasdal, Foss Gård
Leif Kjetil Skjæveland, Skretting
Leo Morf, Environmental Agency of Canton Zurich
Margrét Alsvik, Kontali
Ola Hanserud, EcoDo
Per Erik Sørås, Trøndelag County Council
Pia Kupka Hansen, Havforskningsinstitutet
Tore Krogstad, NMBU
Torleiv Næss Ugland, TerraMarine
Torstein Kristensen, SCALE AQ
Trude H. Nordli, Sjømat Norge
Vanessa Korsbakken Ivanov, Norwegian Environmental Agency

DISCLAIMER

This report has been produced by the Report Authors referenced above, who take full responsibility for the report's contents and conclusions. While the members of the advisory panel acknowledged on the previous page have provided significant input to the development of this report, their participation does not necessarily imply their endorsement of the report's content or conclusions.

To quote this report, please use the following reference:

Müller, D. B., Las Heras Hernández, M., Pandit, A., Øgaard, A. F., & Reitan, K. I. (2023). *Towards A Circular Phosphorus Economy in Norway*. Technical Report. NTNU Open, Trondheim, Norway.

EXECUTIVE SUMMARY

Phosphorus is a building block for all life and therefore plays an essential role in food production. Currently, large amounts of phosphorus enter the Norwegian food system from abroad in the form of mineral fertilizer, feedstuff, food, as well as micro-ingredients for animal feed, mainly in salmon farming. However, only a small fraction of this phosphorus ends up as food for humans, while the largest part accumulates in soil and water systems. This inefficiency entails two challenges:

1. Phosphorus supply is critical. Phosphate rock, the primary source of phosphorus for fertilizer and micro-ingredient production, is a limited resource that is highly concentrated in a few countries. Over 80% of global phosphate rock reserves are found in only 5 countries, and ~70% are located in Morocco and Morocco-occupied Western Sahara[1]. The high concentration renders many countries vulnerable to geopolitical and economic instabilities and threatens food safety. The EU has therefore included phosphate rock on its list of Critical Raw Materials[2].
2. The accumulation of phosphorus in water systems can lead to eutrophication and dead zones, threatening fish stocks and other aquatic life. The high phosphorus concentration in soils due to overfertilization over long periods of time increases the danger of losses to water systems by runoff, further exacerbating the eutrophication risk.

A more circular use of phosphorus could simultaneously reduce supply and pollution risks. This is particularly relevant in Norway, where the government has an ambition to increase salmon and trout production from currently 1,5 to 5 million tons by 2050.

Achieving a circular phosphorus economy is a complex task: (i) The land- and the sea-based food systems are increasingly interlinked, for example through agricultural production of fish feed or the application of fish sludge on agricultural land. (ii) The Norwegian phosphorus cycle is increasingly interlinked with that of other countries as trade flows along the entire food supply chain are growing. (iii) Phosphorus fertilizers, both primary and recycled, are often contaminated with heavy metals such as cadmium, uranium, and zinc, which tend to accumulate in soils. Cleaning the phosphorus cycle is therefore vital for soil fertility and human health.

This report is based on the MIND-P project, which studied the Norwegian phosphorus cycle for both agriculture and aquaculture at a farm-by-farm basis and explored options for increasing circularity. The project identified farm-level and structural barriers to managing phosphorus resources more effectively. We propose four fundamental strategies to overcome these barriers:

1. Develop and maintain a national nutrient accounting.
2. Minimize phosphorus losses and accumulations at farm level.
3. Establish infrastructures for capturing, processing, trade, and use of manure and fish sludge to produce high-quality recycled fertilizers that are tailored to the needs of the users in Norway and abroad.
4. Adopt a regulatory framework to promote a market for recycled fertilizer.

The strategies proposed here were developed with the support of an Advisory Panel consisting of representatives from government, industry, industry associations, and NGOs in an online and two physical workshops conducted in 2022.

THE MIND-P PROJECT

The MIND-P project[3] explored pathways for Norway to become independent of primary phosphorus fertilizer imports and to reduce environmental impacts by utilizing the domestic secondary resources more effectively, focusing on agriculture and aquaculture.

METHODS

1. Study of the Norwegian phosphorus cycle at farm-by-farm level:
    - Spatial distribution of fish sludge and manure generation.
    - Potential for local recycling.
    - Potential for collection, processing, and transport of phosphorus resources for recycling in regions with phosphorus deficit.
2. Analysis of key barriers and opportunities:
    - Lab, greenhouse, and field experiments on the use of recycled sources of phosphorus as a fertilizer.
    - Surveys on consumer acceptance to understand the willingness to accept alternative phosphorus products and systems.
    - Economic barriers to the implementation of alternative systems and technologies.
3. Testing of different strategies and technologies in model simulations and scenarios developed in close collaboration with key stakeholders.

The MIND-P project focused on tracking phosphorus in the Norwegian food production system. It did not explicitly address (i) food consumption and the use of sewage sludge and household waste and (ii) the linkage of phosphorus flows with contaminants. The connection between circular phosphorus management and hazardous materials management through soil protection, food quality, and water pollution needs to be addressed in subsequent work.

TABLE OF CONTENTS

FIGURES

1 GRAND CHALLENGES OF THE ANTHROPOGENIC PHOSPHORUS USE

In a message to United States Congress on Phosphate for Soil Fertility in 1938, President Franklin D. Roosevelt underscored the importance of phosphorus: "I cannot overemphasize the importance of phosphorus not only to agriculture and soil conservation, but also to the physical health and economic security of the people of the Nation." And he added, "it was high time for the Nation to adopt a national policy for the production and conservation of phosphates for the benefit of this and coming generations"[4].

National policies for the production and conservation of phosphorus are still lacking, also in Norway, but the importance of phosphorus has not declined. While Roosevelt mainly addressed the resource conservation, Rockström et al. 2009 raise concerns for the environment[5]. In their landmark publication "Planetary Boundaries: Exploring the Safe Operating Space for Humanity", they discuss the impact of phosphorus flows to the ocean as a key driver for ocean anoxic events (OAE) and as a slow driver influencing anthropogenic climate change at the planetary level.

The current anthropogenic use of phosphorus is largely linear[6] resulting in two major challenges:

Most of the phosphate rock mining is highy concentrated in a few regions. Economical barriers and geopolitcal influence could restrict the access to fertilizers, threatening national food safety[7]. The use and import of mineral phosphorus must be limited if its availability and quality for future generations is to be ensured.

Large amounts of phosphorus accumulate in soil, seabed, and water bodies, contributing to oxygen depletion and dead zones as a consequence of eutrophication[6,8]. The safe operating space for humanity requires a reduction in P flows to water bodies. The qualities of soil and water are further threatened by contaminants associated with primary and secondary phosphorus fertilizers.

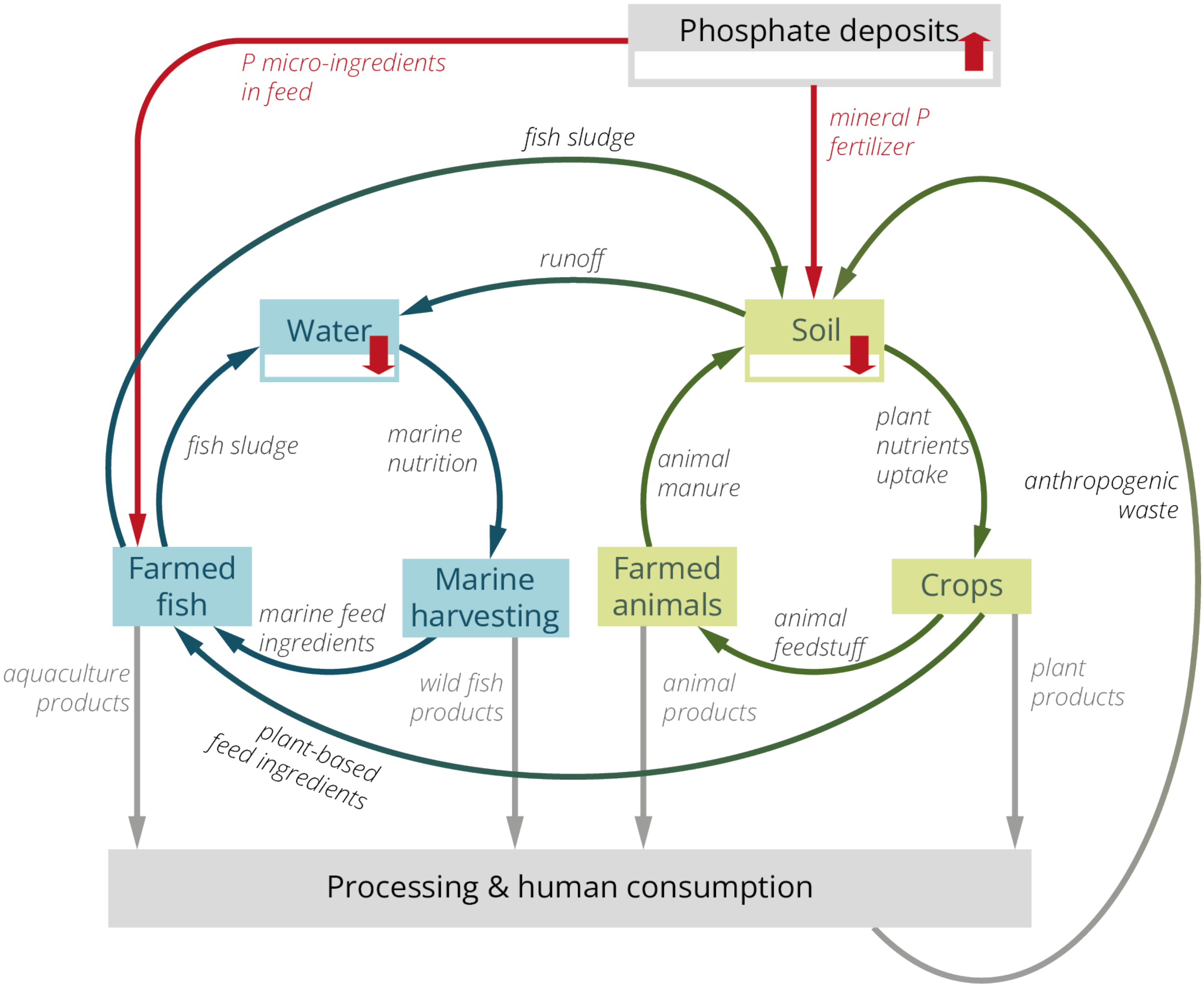


Figure 1: Global anthropogenic phosphorus (P) cycle. Red arrows indicate mineral P additions to the cycle. Red thick arrows indicate P resource depletion or accumulation within a process.

2 THE NORWEGIAN PHOSPHORUS CYCLE

Animal farming and aquaculture are the key drivers of the phosphorus cycle in Norway[9,10]. The Norwegian bioeconomy's use of phosphorus is inefficient and relies on a large inflow of phosphorus from abroad in the form of mineral fertilizer, animal feed, fish feed and food. Phosphorus exports, mainly as fish, are much smaller[10]. The constant addition of imported phosphorus into the Norwegian phosphorus cycle causes an accumulation in soil, seabed, and water bodies[10,11].

2.1 CHALLENGES

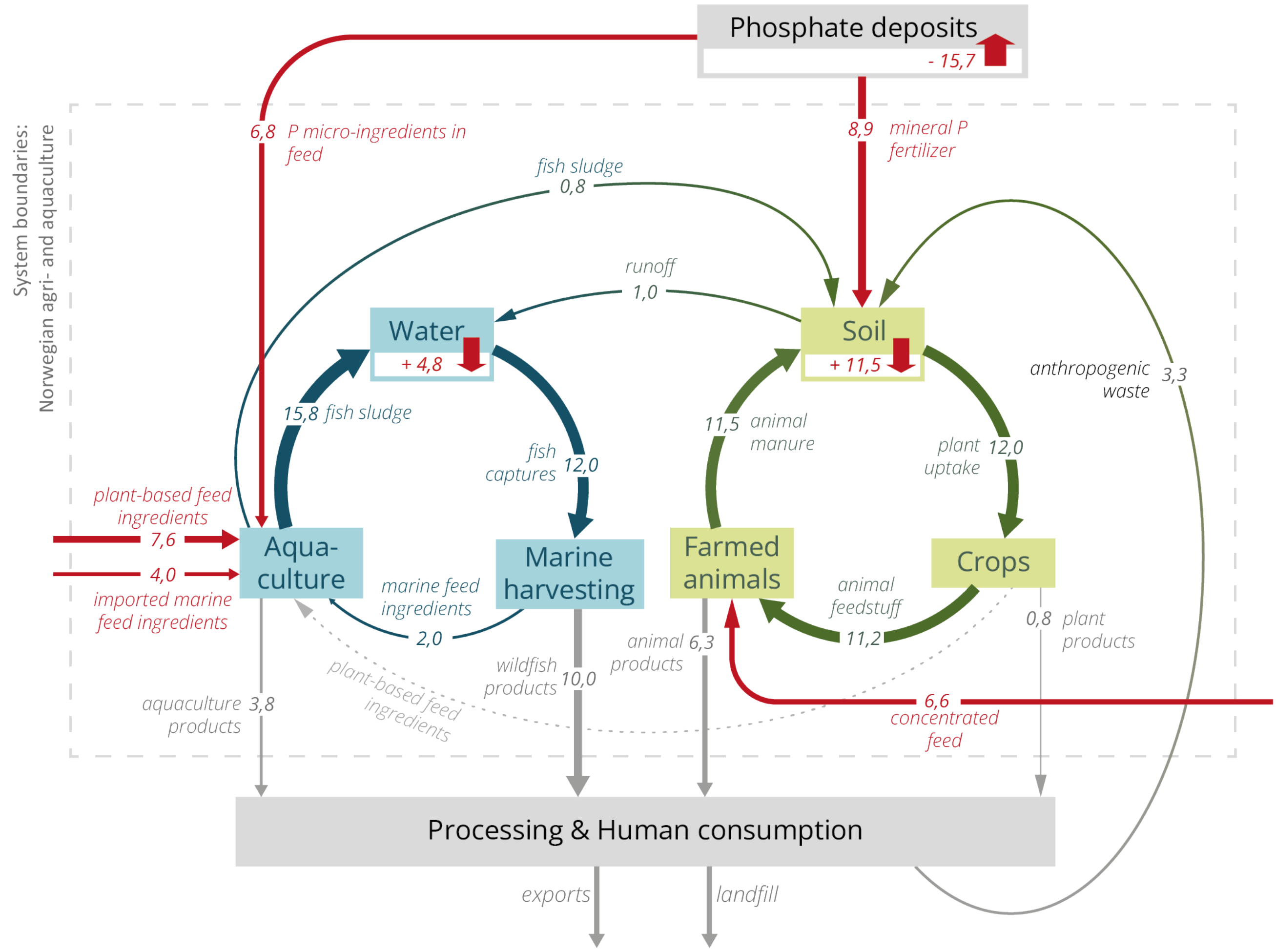


Figure 2: Norwegian P cycle and its challenges [kt P/yr]. Agriculture: average 2017 – 2019, Aquaculture: 2021]. Red arrows indicate the main streams of phosphorus import to the Norwegian cycle. Dotted arrows indicate potential new flows of phosphorus within the Norwegian P cycle.

— **Agriculture** imported ~19,6 kt P/yr in the form of mineral fertilizer, concentrated feed, fish sludge, and other wastes. The outflows from agriculture consist of raw plant and animal products and runoff, which amount to ~8,1 kt P/yr. The difference of ~11,5 kt P/yr is accumulation in the soil. The raw plant and animal products (~7,1 kt P/yr) accounted for about 36% of the total input into agriculture, while the remainder was either accumulating in soils (59%) or lost to water sytstems (5%)[11].

- The accumulation in the soil (~11,5 kt P/yr) tends to become partly unavailable for plants and is partly washed out as runoff into water bodies (~1 kt/yr)[6], where it poses a risk for eutrophication.

- Aquaculture used ~20,4 kt P/yr in the form of feed ingredients (mainly soy from Brazil, but also marine ingredients) and micro-ingredients (mineral phosphorus), which is slightly more than agriculture used. Of this input, 19% (~3,8 kt P/yr) was turned into raw aqua-culture products, 4% (~0,8 kt P/yr) into collected fish sludge - assuming a 70% collection efficiency, and 77% (~15,8 kt P/yr) into fish sludge directly released to the water body[12]. Phosphorus emissions to the water are exacerbated by the fact that salmon, as a carnivore, cannot digest phosphorus in plant-based feed ingredients. For this reason, additional mineral phosphorus is added to the feed as micro-ingredients. Sludge is currently mainly recovered in smolt production facilities, which constitute about 6% of the total sludge produced.

- Fisheries extracted ~12 kt P/yr from the water bodies in the form of fish captures. This partly offsets the not collected fish sludge from aquaculture (~15,8 kt P/yr) and the runoff from agriculture (~1 kt P/yr), resulting in a net accumulation in water bodies of 4,8 kt P/yr. Since fisheries and aquaculture operate in different locations, we cannot conclude that fisheries offset the impact of aquaculture.

Agriculture and aquaculture activities in Norway required imports of mineral phosphorus and feed ingredients of ~15,5 kt P/yr and ~18,4 kt P/yr. The use of these imports resulted in a soil accumulation of ~11,5 kt P/yr and a net inflow to water bodies of 4,8 kt P/yr if the offset of fisheries is included, or of 16,8 kt P/yr without considering the offset.

Phosphorus use in aquaculture has reached levels similar to those of agriculture. Given the goal of the Norwegian industries to increase annual salmon production from 1,5 to 5,0 million tons per year by 2050[13,14], the Norwegian phosphorus cycle is set to become dominated by aquaculture in the coming decades. This entails a growing exposure to risks of mineral phosphorus supply disruptions and emissions unless fundamental changes are made towards a circular phosphorus management.

Colourbox.dk/Galyna Andrushko

Colourbox.dk/Pressmaster

3 RECOMMENDATIONS FOR A CIRCULAR PHOSPHORUS BIOECONOMY IN NORWAY

Establishing a circular bioeconomy is essential for protecting the environment and the industries that depend on it. This is a challenging task that requires a systemic learning approach (Figure 3) and coordination between all key stakeholders, including production and consumption. Here we present recommendations based on a phosphorus accounting of the food production system, while the consumption is not addressed. Physical accounting of nutrients enables the stakeholders to identify the most effective strategies (e.g., through scenarios) and to monitor the progress of the implemented interventions.

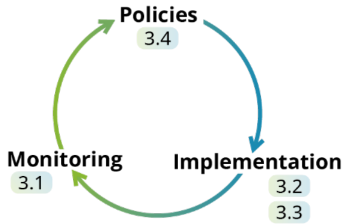


Figure 3: Systemic learning approach for establishing a circular bioeconomy. Numbers refer to sections below.

		KEY ACTORS
3.1	Develop and maintain a "National Nutrient Accounting" for the bioeconomy at different spatial scales.	Norwegian Environmental Agency Statistics Norway Brønnøysund Register Centre Norwegian Food Safety Authority Norwegian Agriculture Agency County administrations
3.2	FARM INTERVENTIONS Maximize the phosphorus utilization in agriculture and aquaculture and reduce waste.	Norwegian Farmer's Union Norwegian Farmers and Smallholders Union Norwegian Seafood Federation Norwegian Agricultural Extension Service
3.3	REGIONAL INTERVENTIONS Develop and implement new technologies and practices for capturing, processing, trade, and use of manure and fish sludge. The aim is to produce high-quality recycled fertilizers that are tailored to the needs of the users in Norway and abroad.	Norwegian Directorate of Fisheries Innovation Norway Industry & Industrial clusters Farmers Norwegian Agricultural Extension Service
3.4	Adopt a regulatory framework including financial instruments to promote a market for recycled fertilizer and transform the food production systems.	Norwegian Environmental Agency Norwegian Directorate of Agriculture Norwegian Directorate of Fisheries Norwegian Food Safety Authority

3.1 DEVELOP AND MAINTAIN A NATIONAL NUTRIENT ACCOUNTING

Why?

The transformation towards a circular bioeconomy is a complex task that affects all actors in the food chain. Changes made by individual actors can have consequences for other actors. Understanding these systemic linkages through a nutrient accounting is essential for recognizing synergy potentials and avoiding undesirable side effects.

How?

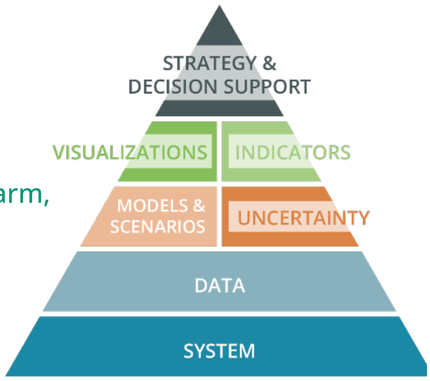


Figure 4: Hierarchy of information in a nutrient accounting system[15]. For more information, see https://minfuture.eu/.

- **Establish a digital infrastructure for monitoring the physical dimension of the Norwegian bioeconomy, including nutrient cycles (carbon, nitrogen, phosphorus) and linkages with hazardous substances at different scales (farm, regional and national):** A national nutrient accounting system could serve as an interactive tool for informing circular bioeconomy strategies for private and public stakeholders. Ideally, the monitoring is harmonized at international level to facilitate research and understanding of secondary fertilizer markets.

- **Use an explicit system approach to inform the monitoring and reporting:** The data collected and reported today often lacks information about the reference points of the data (bottom layer in the pyramid in Figure 4). Metadata that define the measurement points in a system context can improve the robustness and the usability of the data (higher layers in the pyramid).

- **Use the nutrient accounting to inform decisions and planning:** Farmers can use the farm-level nutrient accounting to inform nutrient plans, while policy makers can use aggregate data to inform policies. The nutrient accounting based on national statistics and literature (current status of MIND-P) will ideally be improved, refined, and updated by the farmers. This will improve analysis at farm-level as well as at municipal, regional, and national scales. Such a "living data infrastructure" could improve the knowledge base and facilitate learning.

BARRIERS	OPTIONS TO OVERCOME THE BARRIERS
The entity owning the digital infrastructure can influence its accessibility, limiting its usability for other stakeholders.	A public ownership of the digital infrastructure could ensure a balance between accessibility and confidentiality.
Confidentiality issues could defer actors from committed and accurate reporting activities, which may limit the robustness of the infrastructure.	A lean, effective, and user-friendly data infrastructure can improve data quality and facilitate fertilization and feeding plans as well as reporting.
Incentives or regulations may be necessary to encourage private actors to engage in more reporting activities.	Training programs in the use of the data infrastructure could ensure that the users have ideal benefit, that the quality of the system is guaranteed, and ultimately that the infrastructure is widely used.
The use of the data infrastructure will require expertise, particularly when uploading new data.	
The administrative effort of reporting can be considered too high for industry.	

3.2 FARM INTERVENTIONS: minimize phosphorus losses

WHY?

In agricultural farms, several factors contribute to the inefficiency of phosphorus use: Recycled fertilizers, including manure, tend to be rich in phosphorus, but poor in nitrogen compared to plant needs. If they are applied according to their nitrogen content, as is common practice, the soil receives more phosphorus than the plants can take up, and phosphorus is accumulating in the soil. The seasonality and area of manure applied to cropland is often determined by ease of application and storage capacity, resulting in suboptimal fertilization, compounding phosphorus surplus in soils. Furthermore, soil management, manure spreading practices, and hydrological conditions affect the susceptibility to erosion and runoff.

In aquaculture farms, there are also multiple reasons for phosphorus losses. The challenge that salmon cannot digest phosphorus from plant-based ingredients is currently solved by adding digestible forms of phosphorus as a micro-ingredient to the feed. This increases both the use of primary phosphorus resources and the losses. Furthermore, current fish farming is mainly based on open cage systems where feed losses and fish excrements are lost to surrounding waters and seabed.

HOW?

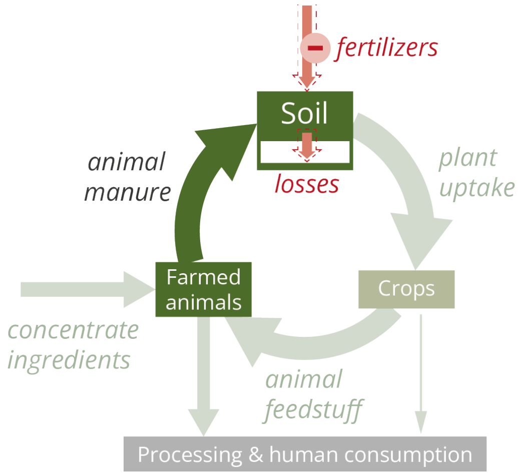


Figure 5: Intervention at animal farm level to reduce P losses.

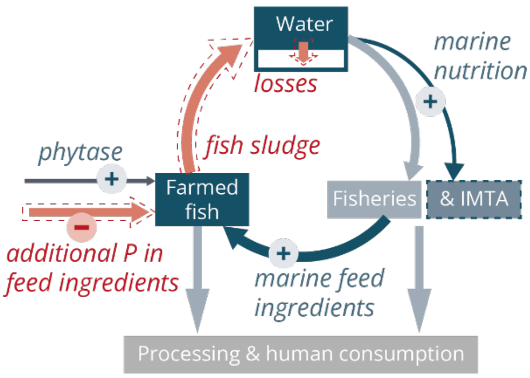


Figure 6: Intervention at fish farm level to reduce P losses.

AGRICULTURE

- Precision fertilization considers the plant's nutrient requirement and soil's nutrient supply for all nutrients (N, P, K), and tailors the fertilizer mix to meet the demand and avoid surplus. When using recycled fertilizers, their high phosphorus content needs to be balanced with additional nitrogen sources according to the specific plant requirements to ensure a balanced supply of all nutrients.

- Optimize the seasonality for manure spreading: The manure should be spread in the growth season to optimize the plant utilization of the nutrients. This requires sufficient manure storage capacity and stricter regulation when spreading is allowed.

- **Optimize the spatial distribution of manure spreading**: manure should be spread over an area large enough to avoid overdosing of P. This can involve that manure needs to be transported over longer distances or to areas that are difficult to access. Hence, this may require suitable infrastructures and technologies for transport and distribution.

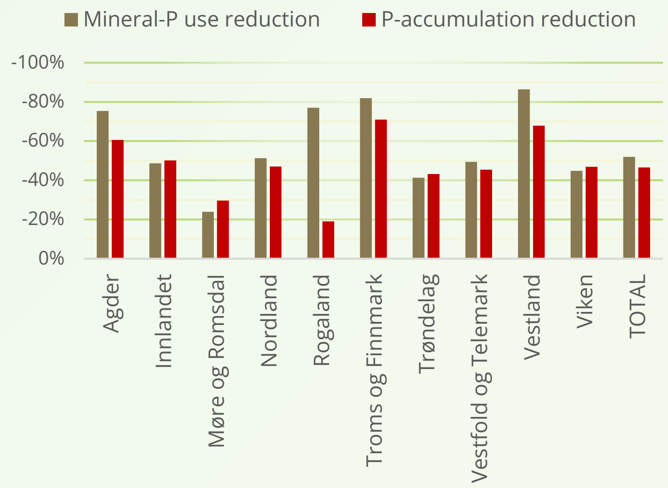


Figure 7: Mineral-P and P-accumulation reduction potential per county.

FARM-LEVEL POTENTIAL TO REDUCE MINERAL-P DEPENDENCY AND P ACCUMULATION IN SOIL

The potential of farm-level interventions to reduce mineral phosphorus use differs significantly by county. For Norway as a whole, mineral phosphorus imports could be reduced by ~4,4 kt/yr (-51%)[11].

The potential to reduce soil accumulation of phosphorus also varies markedly by county. Regions with many farms that combine crop and animal production have a higher mitigation potential. At national scale, the reduction potential is 43%[11].

AQUACULTURE

- **Phytase in fish feed:** Adding the enzyme phytase to fish feed can enhance the bioavailability of phosphorus from plant origin[16], allowing for a reduction of both mineral phosphorus demand and emissions to the sea.

- **Modify feed ingredients:** Introducing feed ingredients that can be effectively digested by the fish, such as northern krill or zooplankton, could also simultaneously cut mineral phosphorus demand and emissions[17].

- **Integrated multi-trophic aquaculture:** IMTA is based on the principle that one species feeds on the waste products of another[18,19]. Phosphorus emissions could be captured and used by other marine organisms. If IMTA products are used to replace agricultural plants in the feed, this has a potential to reduce both mineral phosphorus dependency in feed production and accumulation in water.

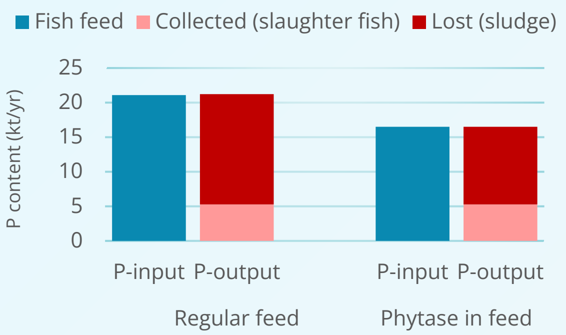


Figure 8: Effects of P demand and emissions after addition of phytase on feed.

ADDING PHYTASE TO THE FEED HAS A LARGE POTENTIAL TO REDUCE MINERAL P DEPENDENCY AND EMISSIONS

Adding phytase to the feed could diminish the need for mineral phosphorus in micro-ingredients by up to ~4,6 kt/yr[12]. Thus, phosphorus discharge to surrounding waters could also be reduced by ~4,6 kt/yr while maintaining current fish production[12].

BARRIERS

Many farm-level interventions are expensive and may require new practices, which may reduce their acceptance.

Changing fertilization practices at farm-level may require investments in new infrastructures to process and distribute manure. Conversely, establishing centralized manure processing facilities could reduce the need for on-farm infrastructure. Investments in either direction could prevent the development of the other or result in underutilized infrastructures.

Challenges related to the current phosphorus management in aquaculture receive little attention and are low on the political agenda.

The costs of phytase and new feed ingredients may hinder their incorporation in fish feed mixes.

New feed ingredients introduce the risk of problem-shifting to new areas and trophic levels (e.g. krill-based meals could alter ecosystems in polar seas[20]).

Deployment of IMTA requires large areas of ocean space in already contained regions such as the Norwegian fjords, competing with already existing uses.

IMTA production requires a high degree of knowledge about the site's surrounding ecosystems. Potential issues related to interference with local wildlife are geographically dependent and not sufficiently studied.

OPTIONS TO OVERCOME THE BARRIERS

Efficient phosphorus resource management is likely to become economically beneficial in a context of increased prices and new regulatory frameworks.

Raising awareness of the importance of the efficient use of nutrients coupled with economic incentives could contribute to an overall optimization of the resource consumption.

Extension services, training programs, and collaboration with agricultural and aquaculture stakeholders could facilitate the adoption of best phosphorus management practices.

Processing the collected manure in centralized plants could reduce the need for on-farm manure storage solutions and ease the handling of residues.

Infrastructure sharing, such as centralized processing facilities, could reduce costs and improve the overall efficiency of phosphorus recycling.

Converting the collected manure and fish sludge into high-quality fertilizers with low water content could reduce the need for investments in new spreading technology and infrastructures.

Research into efficient and low-impact IMTA deployment could potentially enable an aquaculture production with minimal emissions and lower import dependency.

3.3 REGIONAL INTERVENTIONS: establish a collecting, processing and trade infrastructure for manure and fish sludge

WHY?

Farm-level optimization is insufficient to prevent phosphorus losses[11,12] (Figure 7). The reason is that some farms and regions have a surplus of secondary phosphorus while others have a deficit that is covered by mineral fertilizer. For example, coastal areas often have a great potential for fish sludge recovery, however, coastal areas tend to have also a high animal density[11,12], exacerbating their surplus (Figure 8). A trade of manure and fish sludge could help balance supply and demand.

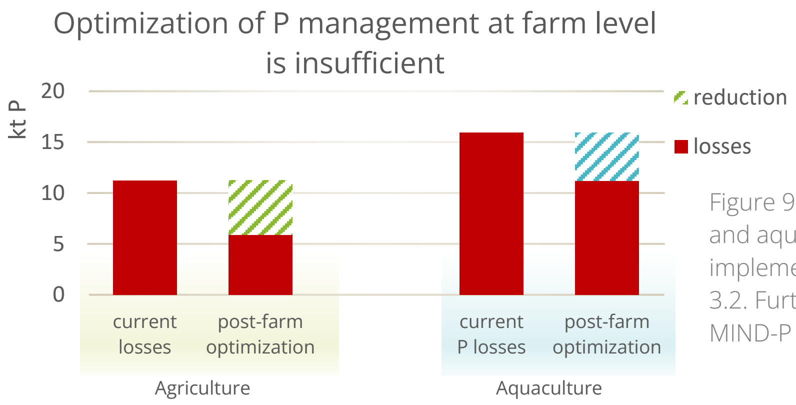


Figure 9: Phosphorus losses in agriculture and aquaculture: Current status and after implementation of measures discussed in 3.2. Further assumptions are discussed in MIND-P publications[11,12].

HOW?

CAPTURING FISH SLUDGE

- **Recirculating Aquaculture Systems (RAS):** Land-based systems, including recirculation aquaculture systems and flow-through systems, that allow for sludge collection and treatment. They are suitable for smolt and grow-out production and allow for the collection of all forms of phosphorus (DIP, DOP, PP)*.
- **Offshore Closed-Containment Systems (CCS):** New offshore technology that controlls water inflows and outflows. This technology has a potential to collect particulate phosphorus (PP).
- **Open-net mechanical Collection Systems (OCS):** Cleaning systems that can be installed in existing open pen systems. They can partially capture particulate waste (PP).

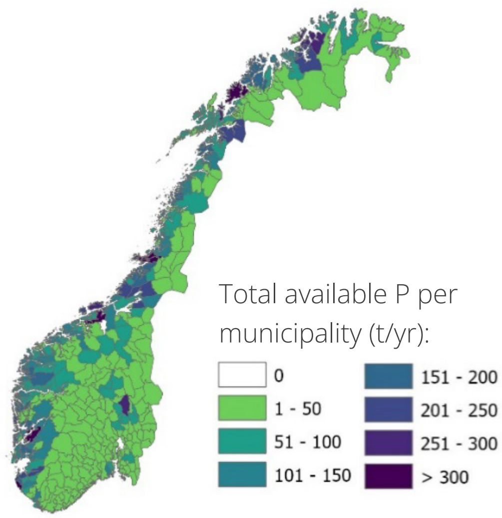


Figure 10: Total phosphorus available from generated manure and fish sludge.

*DIP: dissolved inorganic phosphorus, DOP: dissolved organic phosphorus, PP: particulate phosphorus

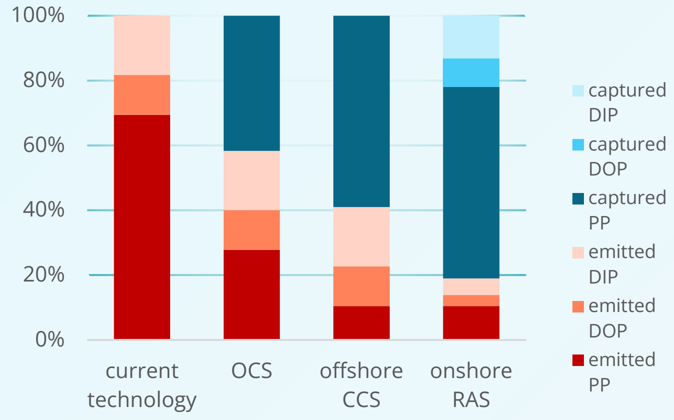


Figure 12: sludge collection potential from different strategies

COLLECTION POTENTIAL FROM DIFFERENT TECHNOLOGIES[8]

Current deployment of fish sludge collecting technologies is marginal[18]. Among the three technologies, RAS has the highest collection potential and is the only technology that can collection of all forms of phosphorus (DIP, DOP, and PP).

However, RAS requires large land area, is energy intensive, and requires large amounts of water[17], while CCS and OCS can be implemented in existing localities.

PROCESSING & TRADE HIGH-QUALITY FERTILIZERS (from manure and fish sludge)

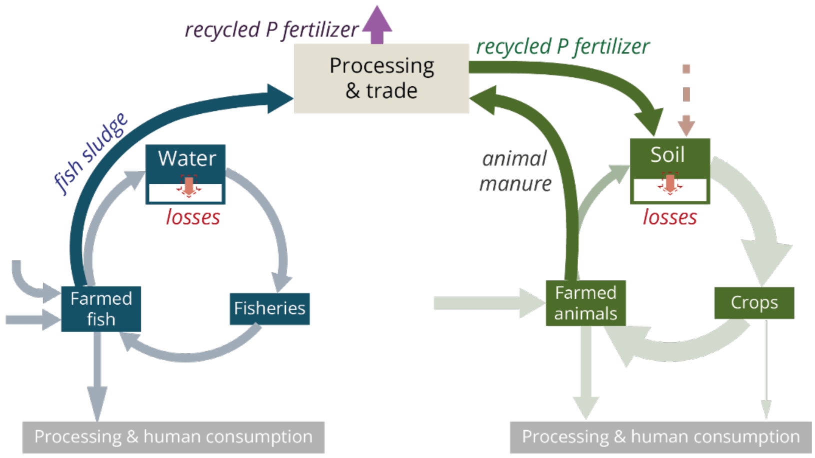


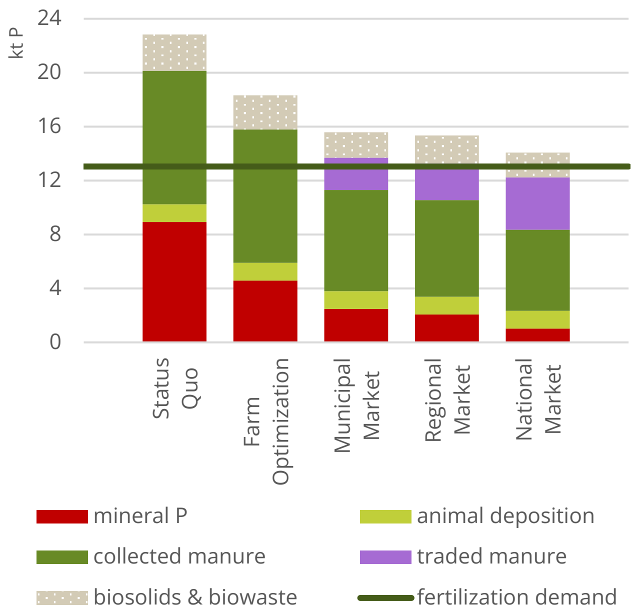
Figure 11: Intervention at regional level to collect, process and trade manure and fish sludge.

- **Dewatering and drying:** Manure and fish sludge contain a lot of water. Dependent on the filter system, collected fish sludge contains up to 95-99.9% water. The removal of water is critical to reduce transportation costs, to ease application on the field, and to avoid soil damage due to heavy machinery.

- **Cleaning and desalinating sludge:** Fish sludge from seawater aquaculture contains significant amounts of *salt*. Salt is an undesirable component in recycled fertilizers because it interferes with nitrogen uptake, reducing growth and inhibiting plant reproduction. This is particularly critical in regions with low rainfall, where salt can accumulate in the soil. Fish sludge can also contain high levels of *heavy metals* such as zinc and cadmium. These tend to accumulate in the soil over time, can suppress plant growth, and may enter the food chain, which is a concern for human health. Additional risks are associated with *bacteria* and *infectious parasites* that can harm plants, animals, and humans. Avoiding the presence of these components in fertilizers is important to ensure long-term soil fertility and health.

- **Balancing nutrient composition of recycled fertilizers:** Fish sludge, as most other secondary fertilizers, tends to be rich in phosphorus but poor in nitrogen and potassium compared to the nutrient demand of the plants. In addition, the phosphorus in fish sludge tends to be poorly available for plants[21]. Balancing the nutrient content according to plant needs and increasing the plant availability of phosphorus are essential to avoid overfertilization.

Mineral phosphorus fertilizer demand under different manure-trade strategies:



Manure management strategies at farm-level can reduce agricultural mineral phosphorus demand in Norway by up to 50%[11]. Combining farm-level optimization with a manure processing infrastructure and a national trade of recycled fertilizer could reduce mineral phosphorus demand to 1 kt P/yr while also avoiding over-fertilization. Note that this balance does not include fish sludge.

Figure 13: Phosphorus fertilization strategies for Norway[11]. Amounts are modelled as averages per year for the period 2017-19.

Use of fish sludge as phosphorus fertilizer in Norwegian agriculture:

Norwegian aquaculture has a potential to collect sludge containing ~5-11 kt P/yr, depending on the collection system. The mineral phosphorus demand is currently ~9 kt/yr, but could be reduced to ~1 kt/yr if agriculture optimizes manure use at the national level. Hence, using fish sludge in domestic agriculture needs to be carefully coordinated with agricultural strategies to avoid phosphorus accumulation in the soil. In addition, alternatives to domestic use of fish sludge as fertilizer need to be explored. These include international markets for recycled fertilizers or the production of Lithium Iron Phosphate (LFP) batteries. The strategy chosen for the use of manure, fish sludge, and other organic wastes will have a significant impact on the size, scope, and spatial distribution of the processing infrastructure to be developed.

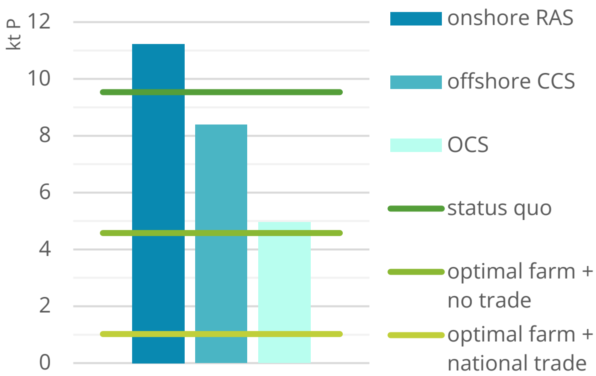


Figure 14: Potential phosphorus supply from fish sludge collection compared with mineral phosphorus demand for different manure use strategies in Norway[11, 12]. Amounts for aquaculture are modelled based on 2021 production levels, agriculture on averages 2017-19.

BARRIERS	OPTIONS TO OVERCOME THE BARRIERS
RAS require large investments and consume a lot of energy during operation. They also impact surrounding ecosystems due to high freshwater need and land use[22].	Research on aquaculture farm placement and sludge collection techniques is needed to identify optimal location-specific strategies.

The collected sludge needs to be transported to processing facilities. This requires large infrastructures that differ for onshore and offshore solutions.

Severe weather events such as strong winds, currents, or waves can restrict the deployment of CCS and open-net collection systems[23].

The greatest potential for secondary phosphorus fertilizer production in Norway lies along its coastline, which is distant from the areas with the highest fertilizer demand[11].

Farmers who are currently using mineral phosphorus need to be convinced that secondary fertilizers are safe, effective, convenient, and don't add to their costs.

Norway's potential to recover recycled phosphorus fertilizer is significantly higher than its phosphorus fertilizer demand[11,12].

Exporting recycled fertilizer to countries with less stringent environmental standards may involve risks of inferior processing, inefficient use, and pollution abroad[24].

Research and development of high-quality recycled fertilizers could increase confidence in recycled fertilizer products and enable national and international markets.

High-quality fertilizer that can be tailored to the farmers' needs could increase acceptance.

A regulatory framework for recycled fertilizers could facilitate trade and responsible use of these resources.

A sales obligation on fertilizer suppliers to sell a given percentage of recycled fertilizer could create a levelled playing field for recycled fertilizers.

Establishing international trade links for recycled fertilizers could help avoid phosphorus accumulation in Norwegian soil and water systems.

3.4 ADOPT A REGULATORY FRAMEWORK FOR THE TRANSITION TO A CIRCULAR PHOSPHORUS ECONOMY

WHY?

The transition to a circular phosphorus economy encounters many barriers. Overcoming these barriers is a multi-stakeholder challenge in which actors with different interests need to coordinate their actions. A poorly coordinated transition risks to bring about poorly used and thus expensive infrastructures, products with a wide range of quality, uncertainty among the users and poor acceptance of the recycled fertilizers; in short: more expensive and less effective solutions. A regulatory framework could facilitate a critical level of coordination to ensure high qualities for products and functioning markets while keeping investment costs low. Organic fertilizers tend to have a financial disadvantage compared to primary fertilizers, particularly when demanding high-quality or clean recycled fertilizers. The regulatory framework therefore needs to include financing instruments to create a level playing field for all fertilizers.

How?

A regulatory framework could provide requirements and guidelines to incentivize stakeholders to adopt technologies and practices for improving resource efficiency. Involving the key stakeholders (including food producers, agriculture and aquaculture organizations, environmental experts) in the development of the framework could facilitate coordination by establish transparency and trust. Cooperation can be further facilitated by the national nutrient accounting system (see 3.1). It can be used, in combination with models, (i) to test the effectiveness of alternative strategies, (ii) to monitor the effectiveness of the implemented strategies, and (iii) to refine the framework in an iterative process. The framework aims at establishing national markets for recycled fertilizers by defining obligations in the action points (1-4) described below.

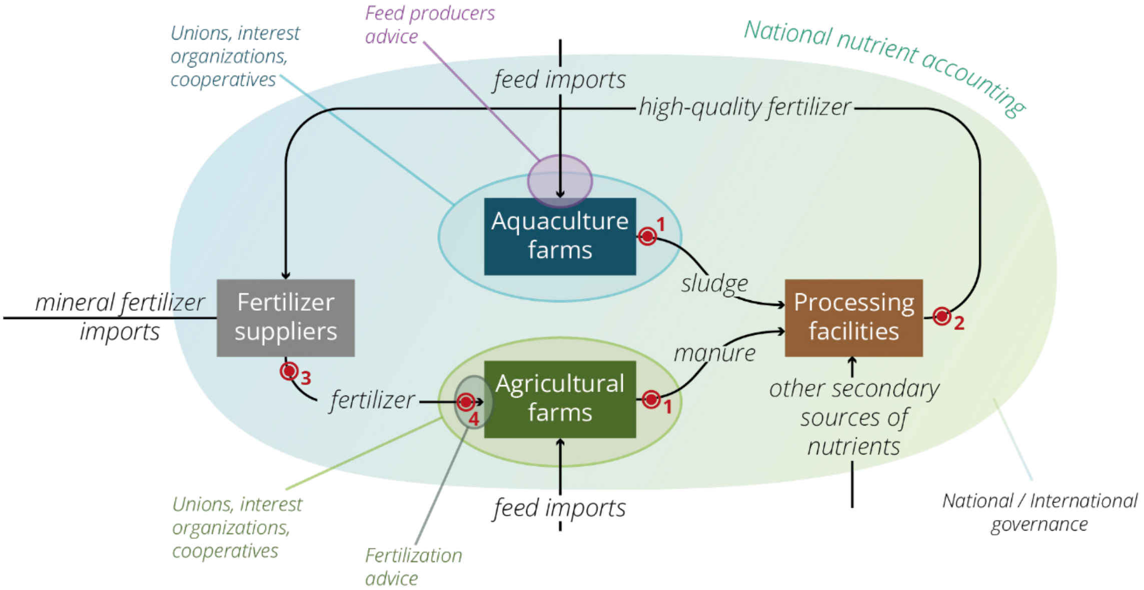


Figure 15: Key stakeholders (boxes), their connections (arrows), and critical action points (red dots) in a regulatory framework for a circular bioeconomy.

1 Aquaculture and agriculture farms: Defining *maximum levels of emission to water and accumulation in soil* could reduce pollution and resource losses while ensuring secondary resource availability. This would be an indirect collection obligation.

2 Manure and fish sludge processors: An obligation on manure and fish sludge processors to produce recycled fertilizer with specific *quality requirements* could help establish trust with users, promote demand, and safeguard environmental qualities.

3 Fertilizer suppliers: An obligation on fertilizer suppliers to *sell a given percentage of recycled fertilizer* could stimulate the production of high-quality recycled fertilizer. This share needs to be adjusted to the increasing production of secondary fertilizers to ensure the processing and use of the collected phosphorus resources.

4 Agricultural consultants: *Teaching consultants* on optimal use of in-house, purchased recycled, and primary fertilizers is critical for creating a level playing field for all fertilizing products.

4 References

1. Stephen M. Jasinski. *Mineral commodity summaries 2023. Mineral commodity summaries 2023* vol. 2023 132–133 http://pubs.er.usgs.gov/publication/mcs2023 (2023).
2. European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative. (2014).
3. MIND-P. MIND-P. *MIND-P* https://mindp.indecol.no/.
4. Franklin D. Roosevelt. Message to Congress on Phosphates for Soil Fertility. *The American Presidency Project* https://www.presidency.ucsb.edu/documents/message-congress-phosphates-for-soil-fertility (1938).
5. Rockström, J. *et al.* A safe operating space for humanity. *Nature* **461**, 472–475 (2009).
6. Nesme, T. & Withers, P. J. A. Sustainable strategies towards a phosphorus circular economy. *Nutr. Cycl. Agroecosystems* **104**, 259–264 (2016).
7. Desmidt, E. *et al.* Global Phosphorus Scarcity and Full-Scale P-Recovery Techniques: A Review. *Crit. Rev. Environ. Sci. Technol.* **45**, 336–384 (2015).
8. Carpenter, S. R. & Bennett, E. M. Reconsideration of the planetary boundary for phosphorus. *Environ. Res. Lett.* **6**, 014009 (2011).
9. Hamilton, H. A. *et al.* Investigating Cross-Sectoral Synergies through Integrated Aquaculture, Fisheries, and Agriculture Phosphorus Assessments: A Case Study of Norway. *J. Ind. Ecol.* **20**, 867–881 (2016).
10. Hamilton, H. A. *et al.* Recycling potential of secondary phosphorus resources as assessed by integrating substance flow analysis and plant-availability. *Sci. Total Environ.* **575**, 1546–1555 (2017).
11. Las Heras Hernández, M. *et al.* Farm-level MFA of the agricultural phosphorus cycle in Norway: informing resource efficiency strategies at different regional scales. *Planned* (2023).
12. Pandit, A. *et al.* Spatially and temporally disaggregated mapping of the phosphorus cycle in Norwegian aquaculture for informing circular bioeconomy strategies. *Planned*.
13. Norsk Industri. Veikart for havbruksnæringen. (2017).
14. Sjømat Norge. Aquaculture 2030 – Think globally, act locally. (2017).
15. Daniel Beat Müller *et al.* Maps of the physical economy to inform sustainability strategies. in *HANDBOOK OF RECYCLING: state-of-the-art for practitioners, analysts, and scientist* (ELSEVIER - HEALTH SCIENCE, 2023).
16. Kumar, V., Sinha, A. K., Makkar, H. P. S., De Boeck, G. & Becker, K. Phytate and phytase in fish nutrition. *J. Anim. Physiol. Anim. Nutr.* **96**, 335–364 (2012).
17. Olsen, R. E. *et al.* Can mesopelagic mixed layers be used as feed sources for salmon aquaculture? *Deep Sea Res. Part II Top. Stud. Oceanogr.* **180**, 104722 (2020).
18. Ellis, J. & Tiller, R. Conceptualizing future scenarios of integrated multi-trophic aquaculture (IMTA) in the Norwegian salmon industry. *Mar. Policy* **104**, 198–209 (2019).
19. Wang, X., Olsen, L., Reitan, K. & Olsen, Y. Discharge of nutrient wastes from salmon farms: Environmental effects, and potential for integrated multi-trophic aquaculture. *Aquac. Environ. Interact.* **2**, 267–283 (2012).
20. Almås, K. A. *et al. Bærekraftig fôr til norsk laks*. https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/2758913/Rapport+B%C3%A6rekraftig+f%C3%B4r+til+norsk+laks.+2020.pdf?sequence=1.
21. Brod, E. & Øgaard, A. F. Closing global P cycles: The effect of dewatered fish sludge and manure solids as P fertiliser. *Waste Manag.* **135**, 190–198 (2021).
22. Ahmed, N. & Turchini, G. M. Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *J. Clean. Prod.* **297**, 126604 (2021).
23. Clarke, R., Maitland, D. & Bostock, J. Technical Considerations of closed containment sea pen production for some life stages of salmonids. 169 (2018).
24. Schröder, J. J., Smit, A. L. & Rosemarin, A. *Sustainable use of phosphorus*. https://edepot.wur.nl/163942 (2010).