ESPP SCOPE Newsletter n°158 – December 2025

Phosphorus sustainability in aquaculture

ESPP's second thematic workshop on sectoral nutrient sustainability, on aquaculture, took place in Bergen (Norway) and online, 10th – 12th June, co-organised by ESPP, NORCE Research AS, Innoaqua Horizon R&D project, Ragn-Sells (Aquaphoenix Horizon project), NCE Aquaculture Cluster, NIBIO and the UNEP-funded project uPcycle.

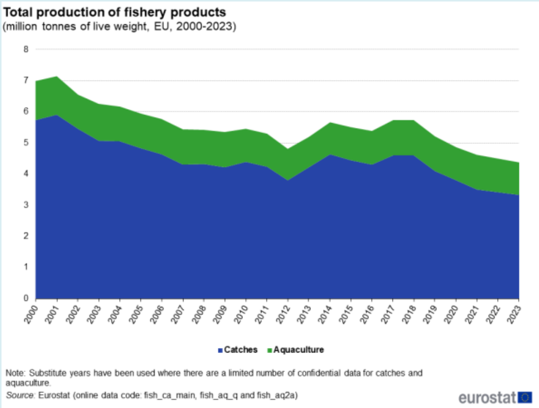
This aquaculture workshop follows a first thematic workshop on phosphorus in livestock production, co-organised with Timac – Roullier and ESPP in Saint Malo, March 2025. This first workshop is summarised in ESPP's SCOPE Newsletter n°155, including a one-page outline of key policy messages on nutrient stewardship in livestock, developed at the workshop.

Some 70 industry and research experts, stakeholders and policy makers joined the aquaculture nutrients workshop in Bergen, with a further 80 participants connected online.

The workshop was opened by **Robert Van Spingelen, ESPP, Dorinde Kleinegreis, NORCE** and **Ole Arthur Vaage, Ragn-Sells.**

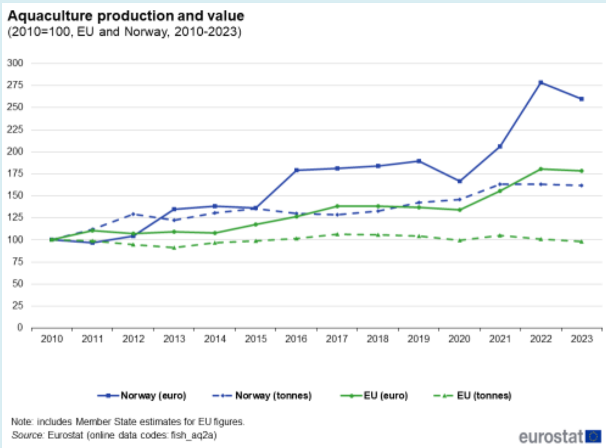
Aquaculture in the EU and Norway

Covering around 2.1% of global production, the EU is the seventh-largest producer of fishery and aquaculture products, behind China, Indonesia, India, Vietnam, Peru, and the Russia.[1]



In 2023, aquaculture farming in the EU yielded almost 1.1 million tonnes of aquatic organisms, worth €4.8 billion, representing just over two-fifths of the total value of the EU's total production of fishery products (landings and aquaculture).[1,2] Production is highly concentrated, with Spain, France, Greece and Italy accounting for more than two-thirds of the total EU's aquaculture output volume in 2023 (66.6%). In general, aquaculture plays a major role in the countries around the Mediterranean Sea and the Black Sea. Finfish (particularly trout, seabream, seabass, carp, tuna and salmon) and molluscs (particularly mussels, oysters and clams) together accounted for almost all of aquaculture production by weight in the EU in 2023. The production of algae and seaweed is an emerging sector of the blue economy, and these are used in food, feed production, industrial and pharmaceutical products. [2]

Norway, though not an EU member, remains Europe's aquaculture powerhouse. The value of aquaculture output in Norway exceeded that of the whole of the EU; Norway produced 1.6 million tonnes of aquatic organisms (almost exclusively salmon), worth €10.0 billion in 2023, and was the world's sixth largest producer in aquaculture fish production in 2022, with a 2.7% global share. It was also the world's second largest exporter of aquatic organisms, after China.[2,3]



Overall, Norway's aquaculture output exceeds that of the entire EU in both volume and value, driven primarily by large-scale, export-oriented salmon farming in the North Atlantic and fjord regions. By comparison, EU aquaculture is more diversified in species and geographically fragmented, with production focused along the Mediterranean and Atlantic coasts and smaller volumes in the North Sea and Baltic regions.

Between 2010 and 2023, the volume of EU aquaculture production remained relatively stable (see Figure on the right). However, the value of this production increased sharply (up 78%) due to higher prices, particularly in 2021 and 2022. Over this same period, there was a sharp increase in both the volume and value of Norwegian aquaculture production. In 2023, the volume of aquaculture production in Norway was 62% higher than in 2010.

Sources: (1) The EU Blue Economy Report 2025; (2) Eurostat (data from March 2025).

Global and EU policies

Will Brownlie, Centre for Ecology and Hydrology, Edinburgh, explained that this workshop on nutrient sustainability in aquaculture will contribute to a chapter in the White Paper Priority Actions for Cross-Sector Phosphorus Sustainability, prepared under the GEF/UNEP uPcycle project. Alongside this chapter, the uPcycle team will also develop a policy brief on nutrient sustainability in aquaculture, which will be disseminated through the uPcycle project and UNEP networks. This policy brief will outline a proposed global mandate for UN member states to address phosphorus sustainability in the aquaculture sector.

Monica Kobayashi, Secretariat of the Convention on Biological Diversity, introduced UNEP policies on nutrients, reminding that nutrients (including phosphorus) are essential for life, and so for healthy and productive aquaculture, but pose problems when in excess in the environment, for instance causing eutrophication. Nutrient pollution causes ecological damage, but also important economic consequences, for example on tourism. Several UN SDGs (Sustainable Development Goals) address nutrient sustainability, in the goal 6 (clean water & sanitation), goal 2 (end hunger), goal 14 (life in water). In the

Kunming Montreal Global Biodiversity Framework (KMGBF), the Target 7 (see ESPP eNews n°74) aims to reduce pollution to levels not harmful to biodiversity. This target include the reduction of pollution from chemicals, pesticides and nutrients.

The KMGBF defines two headline indicators for Target 7 which all countries must report, one is on risk of pesticides and the other is the "Index of coastal eutrophication potential" (this is the same as the SGD indicator 14.1.1a). Additional optional indicators may also be reported: agricultural nutrient losses and waste water treatment.

The KMGBF also includes Target 10 which aims to enhance biodiversity and sustainability in agriculture, aquaculture, fisheries and forestry.

Countries are currently developing national targets, plans and actions to achieve the KMGBF targets and are reporting these to CBD Secretariat. The CBD Secretariat recognises the need to engage with industry sectors such as aquaculture to take forward the implementation of the KMGBF goals and targets.

Derun Yuan, FAO (Food and Agricultural Organisation of the United Nations), highlighted the continuous growth of aquaculture production worldwide, emphasising its critical role in supporting food security, economic growth, local livelihoods and trade. In 2022 fisheries and aquaculture worldwide collectively achieved an all-time high production of 223 million tonnes, with aquaculture production of animal species (94.4 Mt) surpassing fisheries production. FAO projects that total fisheries and aquaculture production, excluding algae, will reach 205 Mt in 2032, a 10% increase from 2022. Most of this growth will come from aquaculture. Aquaculture is recognised as an efficient and environmentally sound pathway for food production. It is essential that environmental sustainability and social responsibility are embedded within this sector's ongoing development.

FAO's "Guidelines for Sustainable Aquaculture" (GSA), formally endorsed by FAO members in 2024 after seven years of comprehensive consultation of stakeholders worldwide, establish a clear vision and framework for sustainable aquaculture globally. The guidelines recommend that States and stakeholders (§5.1.1) "develop and implement national or regional strategies for sustainable use of water, land, genetic resources, and energy that address the needs and challenges of the aquaculture sector. Strategies should emphasise efficient water use and recirculation of water, and facilitate nutrient recovery and reuse to reduce the carbon footprint of aquaculture and integrate it into nutrition-sensitive, circular, and sustainable food systems". They should also (§5.2.6) "develop and promote innovative technologies for nutrient recycling and monitoring from aquaculture effluent to ensure safe reuse within the ecosystem through integrated and circular economy approaches".

Constanza Silva, Chile Department for Fisheries, explained that regulation of aquaculture in Chile is complex because it is partly covered by seven different Ministries or Departments: water (environment), food safety, inland waters, coastal waters, fisheries, research and permitting compliance (interior). Chile has nearly 500 marine fish farms and a further 150 on-land farms, of which only 14 to date are RAS (recirculating aquaculture system). Aquaculture in lakes is decreasing, with fish farms remaining now in only three of Chile's fifteen large lakes.
Author has not reviewed this text.

EU policy and regulation

Lorella De La Cruz Iglesias, European Commission, DG MARE, explained that nutrient management is at the core of EU policy. The Biodiversity Strategy and the Zero Pollution Action Plan set a target to reduce nutrient losses by – 50%. The Commission's "Vision for Agriculture and Food" (COM 2025(75), Feb. 2025, see ESPP eNews n°95) underlines the need to reduce the EU dependency on imported fertilisers and increase the use of recycled nutrients. In terms of aquaculture policy, the European Commission's 2021 Communication on sustainable and competitive aquaculture (COM/2021/236) also covers the need to work on reducing and monitoring emissions of nutrients and organic matter. This Communication states that the Commission will "develop a guidance document on environmental performance in the aquaculture sector" that includes good practices on "how to achieve nutrient-balanced aquaculture sites" and "the circular approach and waste management". The Commission is developing this document and expects that it will be published before the end of the year.

The Commission has also recently requested a document identifying opportunities on the valorisation of side-streams from aquaculture and recommendations to promote a circular approach to this sector. Finally, the Commission mentioned the Partnership on Smart Circular Aquaculture, established as part of Smart Specialisation under the Interreg EU programme. This partnership has, among other objectives, the better use of side streams implementing circular production systems.

Matjaz Klemencic, European Commission DG SANTE, underlined that the EU Animal By-Product (ABP) Regulations are complex as they cover a wide range of industries and materials. The basic rules, as set out in Regulation (EC) No 1069/2009 are robust to ensure food and feed chain safety and can only be modified by co-decision (EU Parliament and Council). However, the implementing rules, defining e.g. processing methods (in Commission Regulation (EU) N. 142/2011 and ITS annexes) are updated regularly by the Commission (several times per year) and the Commission can always consider new questions, where supported by data. Also, importantly, the basic rules allow for Member State national derogations, under conditions: industry should contact national ABP authorities for this. He emphasised that this is not the interpretation of the EU rules, which the Commission has no right to do, (only the courts and ultimately the European Court of Justice), but sharing his understanding as a technical assistance for this forum to help implementation of the EU ABP rules by the stakeholders and authorities, as well as possible further scientific and policy development on the area.

Mr. Klemencic also addressed the different questions raised by ESPP. He indicated that "aquaculture sludge" or "fish sludge" are not defined in EU regulations, in particular not in the Animal By-Products (ABP) Regulations. However, all aquaculture sludge certainly is an ABP (by art. 3.1 (Definitions) of Regulation (EC) No 1069/2009). Also, it is not manure, both because Regulation (EC) No 1069/2009 excludes fish excreta from the definition of "manure" and because it is not only excrement as it contains other materials: uneaten feed, possibly dead fish, leaves, seaweed … Because aquaculture sludge is neither Cat.1 nor Cat.3 then it is ABP Cat.2 (by 1069/2009 Art. 9(h) "animal by-products other than Category 1 material or Category 3 material", and therefore 1069/2009 enables the Commission to define implementing rules (by amendment of 142/2011), that is harmonised (EU-validated) treatment processes and end-points for certain uses, in particular for fertilising products – in which case (after specified processing and possibly subject to other conditions) use could then be authorised by delegated amendment of the annexes of the EU Fertilising Products Regulation 2019/1009 (FPR). This process should start with an EFSA Opinion on the safety of specified uses after specified treatments and under specified conditions, and after this the Commission would consider implementing rules to modify 142/2011 appropriately.

Because aquaculture sludge is an ABP Cat.2, today be used as input to ash, residues from a biogas plant or compost referred to and in accordance with Articles 3(c), 3(b) and 3(a) of Delegated Regulation (EU) 2023/1605 (referring to relevant harmonised processing methods in 142/2011).

Because aquaculture sludge is not "manure", it cannot today be included in EU fertilising products as "Processed Manure" under the conditions of 2023/1605 art. 3(d), nor is included in the other materials cited in Delegated Regulation 2023/1605 art. 4. More generally speaking, it can only be used as laid down in Delegated Regulation (EU) 2023/1605.

DG SANTE has already indicated that industry, if interested, could collect and prepare data to enable EFSA assessment and that when industry has collated sufficient data to hope for a favourable Opinion, then DG SANTE may launch an EFSA mandate. He suggests that industry may wish to collect data on the composition of aquaculture sludges (covering variations in different aquaculture and sludge collection systems and with different cultivated species, definition and standards of the material), intended uses, etc. He suggests that this should cover all aquaculture sludge (not only fish) and that data should in particular address biological safety after treatment and fish pharmaceuticals. He referred to previous exploratory contacts with DG MARE and FEAP (Federation of European Aquaculture Producers) and suggested close cooperation between the stakeholders of this forum with stakeholders represented by FEAP.

Answering questions, Mr. Klemencic indicates that:

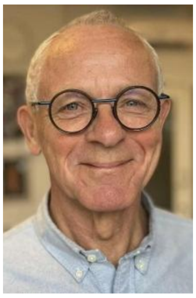
- "Fish meal" is generally Category 3 ABP and is covered by PAP (Processed Animal Protein), for which harmonised processing methods and end points are defined.
- Other Cat. 3 materials from seafood processing and fisheries are covered by general ABP rules: in feed for farmed animals in accordance with art. 14(d)(i) of 1069/2009, for the manufacturing of fertilisers in accordance with art. 32 of the Regulation, or for technical purposes outside the feed chain.
- It is important to note the principles for use of ABPs from food processing industries stemming from the relevant rules, as explained in "Guidelines for the feed use of food no longer intended for human consumption" (2018/C 133/02 link: EUR-Lex - 52018XC0416(01) - EN - EUR-Lex). In particular, any material which has been classified as waste or wastewater, or comes from a waste or wastewater processing stream, cannot re-enter the food chain unless authorised by specific rules.
- Food processing wastewaters from factories processing animal products (e.g. from dairy, fisheries) and materials extracted from such streams are Cat.2 ABPs (art. 9(h) of 1069/2009, cited above).
- 1069/2009 specifies (Art. 2.2(f)) that "shells from shellfish with the soft tissue and flesh removed" are not ABPs. This implies a process of removal by and under the control of an operator, normally a food business operator. If this is the case, even the shells can continue to be considered as a by-product under the control of various operators (e.g. from a food processing site and onwards) and can continue to be processed and valorised under the ABP Regulation (e.g., material into feed or fertilisers production). Alternatively, operators can chose to consider them out of the scope of ABP rules, but in that case those shells must be handled in accordance with EU waste rules excluding many uses (e.g., feed use), while allowing others (e.g. disposed and used in the construction of marine piers).

Chris Thornton, ESPP, explained that stakeholders consider that recycling of nutrients from fish sludge and seafood processing residues today faces regulatory blockages or uncertainties which hinder innovation, investment and implementation.

He noted in particular the following questions:

- Fish excrement is excluded from the Animal By-Products Regulation (ABP, 2009/1069) definition of "manure". This results in confusion as to whether or not fish sludge is or is not an Animal By-Product, and how it is regulated.
- In particular, it is today unclear whether or not fish sludge or other aquaculture sludge can be used under the EU Fertilising Products Regulation (FPR, 2019/1069) as input to CMC3 (compost), CMC5 (digestate), CMC13 (ashes).
- Because fish excrement is not "manure", it is currently excluded from the FPR CMC10 (processed manure).
- There are questions concerning "fish meal" (definition, ABP status, FPR status).
- Valorisation of seaweed, shellfish shells and other seafood processing residues can depend on whether they are classified as "by-products" or as "waste".

  ESPP has compiled a detailed table of regulatory questions concerning aquaculture and seafood residues, online here www.phosphorusplatform.eu/regulatory. This is 'work in progress' and comments and input are welcome to info@phosphorusplatform.eu



Brian Thomsen, Aquaculture Advisory Council (AAC, representing aquaculture operators and other interest groups), indicated that today most of the Danish land-based farming of fish is based on recirculation technology (RAS) and that RAS facilities produce significantly more manure than traditional flow-through farms.

Heavy metals in the form of cadmium and nickel are bound to suspended particles in the water streams and the particles precipitates once the water enters a fish farms. This may lead to elevated levels of heavy metals in manure from notably traditional fish farms and the Danish authorities has historically defined and regulated fish manure from land-based aquaculture as sewage sludge.

The classification as "sewage sludge" limits the use in agriculture and biogas plants, and per example Arla rejects the use of sludge on grazing land for dairy cattle.

Industry asks that these regulatory blockages be addressed by both EU and national authorities. In particular, the AAC has recommended that fish manure should be classified as manure under the EU Animal By-Product Regulation 2009/1069 and a joint advice from AAC and the Marked Advisory Council calls for the ABP regulation to categorise fish excreta as manure.

In December 2024, DG MARE answered that it is exploring the possibilities towards valorising fish sludge as fertilisers with the potential to enter the market of EU fertilising products and that the Commission will prepare an EFSA dossier concerning a biological risk assessment of fish sludge for use in fertilising products and initiate discussions regarding the essential inclusion of fish sludge under the Animal By-Product Regulation.

Torhild Tveito Compaore and **Victoria Røyseth, Norway Food Safety Authority**, emphasised the important potential for fish sludge collection to recycle nutrients. Norwegian companies are eager to start using it for producing fertilisers or input materials for feed production in an international market. They need to take investment decisions and are impatient to see resolved the current blockage of fish sludge valorisation by the EU Animal By-Products Regulations.

Fish sludge from fresh water is already commonly used for fertiliser production in Norway. Norway has new Fertilisers Regulations since February 2025 and fish sludge is authorised for use as a fertiliser under conditions:

- hygienisation and stabilisation are required;
- for seawater fish sludge, an authorisation procedure is required to document that it is line with the regulation for example when it comes to salinity and contaminants;
- specific rules are defined for heavy metals levels, nutrient content.

The Norwegian Food Safety Authority does not consider fish sludge to be an Animal By-Product and considers that freshwater fish sludge is unlikely to contain dead fish because of how systems are operated. Fish sludge is however not authorised in Norway as feed for insects intended for animal feed by application of the Animal Feed Regulation 767/2009 which excludes use of excrements even after treatment (annex III (1)).

The Norwegian authorities consider that technologies for collection of fish sludge in seawater aquaculture are not ready for roll-out and so cannot today be made obligatory. Norway considers that further research and data are needed on the safety of use of fish sludge in fertilisers or as insect feed. The Norway Research Council has published a call for research (see ESPP eNews n°98) including but not limited to:

- fish sludge, manure or kitchen/food waste as substrate for insects to be used as feed ingredient
- integrated multitrophic aquaculture and the potential for transmission of infection between species, and levels of pharmaceuticals and algal toxins.

Veronika Sele, Norway Institute of Marine Research, noted that some insect species are authorised as feed for fish, poultry and pigs (Commission Regulation (EU) 2017/893 of 24 May 2017), but that fish sludge is not defined as a feed and cannot be used as a substrate for insect production. The regulation is based on the EFSA 2015 Opinion "Risk profile related to production and consumption of insects as food and feed" (DOI), which did not assess fish sludge as a feeding substrate. A number of research projects have developed and collated data on characterisation and contaminants in fish sludge, in particular the project FHF 901732 (Securefeed, 2022-2024) leading to a number of publications. These show that some heavy metals in fish sludge may exceed regulatory limits for animal feeds (cadmium, arsenic) and that there are significant levels of other metals and minerals in fish sludge, coming principally from fish feed materials and/or feed additives (copper, zinc, manganese, iron). Aluminium levels found in some cases probably come from use of aluminium salts as flocculants in sludge dewatering. Insects, such as the black soldier fly (BSF) larva, can grow on fish sludge as a substrate. However, some of the contaminants are at risks of bioaccumulating in the insects, e.g. the dioxins and PCBs were found to reach the regulatory limits set for animal feed in the BSF larvae when feeding on fish sludge. Few studies have investigated the bioaccumulation of organic contaminants in insects when given marine-based substrates. Furthermore, in that study pure fish sludge was used as a substrate, which may not be an ideal feed composition for insects.
Data confirms that fish sludge is rich in nutrients, but with wide variations in levels of some contaminants. Further work is needed to understand these variations prior to future usage of fish sludge as a substrate.

Industry engaged for aquaculture nutrient circularity

Pär Larshans, Ragn-Sells, spoke to the workshop direct from the United Nations Oceans Conference in Nice, France. Circularity is being widely discussed at this conference and is seen as a tool to reduce marine pollution

Ragn-Sells is developing processes to recover nutrients from wastes to use in food production. Calcium phosphates recovered from sewage sludge incineration ash are now authorised as a fertiliser in EU certified Organic Farming (EU Regulation 2025/973).

Aquaculture has a key role in the economy of coastal areas and in developing nutritious world food production, but it is essential to ensure sustainable water management, protection of coastal and marine biodiversity and to avoid nutrient pollution. Ragn-Sells is developing processes to recover renewable energy (biogas), clean recycled nitrogen (ammonium salts) and a digestate-based phosphorus-rich organic fertiliser from fish sludge and fish processing.

Torgeir Lassen, Terramarine, Norway. The company is a specialist supplier of organic-based fertilisers, tailored to farmers' needs. Terramarine already includes fish sludges from aquaculture as an input material for its fertilisers. Marine aquaculture fish sludge poses the challenge of salinity reduction before it is used in fertilisers. Terramarine considers that the food chain must become circular, to return organic carbon and nutrients to soils where they are needed. This should be local wherever it can correspond to local agronomic needs, for example with composts. Where local recycling is not possible, then sanitisation and drying are needed to enable transport to regions needing organics to restore soils.

Jon Svenningsen, NCE Aquatech Cluster, Norway, considered that fish farmers are today open to the objective of fish sludge recycling rather than release to the sea, but face a range of technical challenges including: H_2S from sludge handling and storage, difficulties with maintenance (clogging, obstruction by dead fish or external objects), cost of sludge collection, transport and processing. Based on prior reports and assuming 2 million tonnes feed per year with 0,94 % Phosphorus content gives 18,8 million tonnes P in feed. With 75 % of feed not retained in body the total loss/potential for P collection is around 14 000 tP/year. However, actual figures from Norwegian farming indicates that only an amount corresponding to less than 10 % of feed used is collected. With higher P content in faeces (around 2 %) the potential with today's systems might be 10 % of 2 mill tons x 1,5% (P in sludge) = 3 000 tP/year. This is much lower than previous estimates, and the difference is use of actual data: Fine particles and dissolved material are lost to a much larger degree than indicated by technology suppliers' figures.

Marine fish sludge collection reduces nutrient losses, so addressing eutrophication, but can only be rolled out commercially if cost-effective sludge collection, boat transport and processing can be developed, leading to real products corresponding to user needs and with a market (not just spreading on fields).

Erling Bøhn Hilstad, Andfjord Salmon, Norway, presented the company's project for "the world's most environmentally friendly fish farm" on Andoya Island, Northern Norway. After pilot trials, full scale construction is now underway with the objective of producing 90 000 t/y of salmon. This will combine the benefits of seawater with on-land location. A 4.4 km tunnel will supply seawater throughflow to the fish farm from 50m below sea level. The on-land aquaculture pools will allow fish sludge collection. The island's proximity to the Gulf Stream means warmer water in winter. Trials have shown only 2.5% fish mortality. Andfjord is investigating anaerobic digestion of the fish sludge to produce biogas and then recycling of digestate as fertiliser or phosphate recovery.

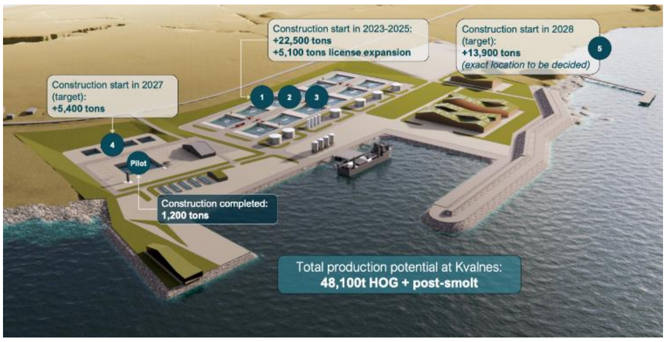


Illustration of a potential facility when finished.

Jostein Iversen, Grieg, underlined that fish farmers' priorities are the quality and health of fish. Reducing salmon "loss" (fish mortality or inadequate quality, leading to low-value uses such as oils or fish-feed) is the priority. Recruitment is a challenge for many fish farms, situated in remote rural areas. Farmers and personnel are motivated by fish husbandry rather than sludge recycling, so outsourcing of sludge management may be preferred.

A **panel discussion** led by **Olav Fjeld Kraugerud, Bellona**, with **Jostein Iversen, Grieg, Ole-Arthur Vaage, RagnSells, Will Brownlie, CEH** and **Erik-Jan Lock, Nofima** discussed the need to ensure coherence of different policies relevant to phosphorus in aquaculture, to reduce nutrient losses to the environment, ensure optimum use of bio-resources and recycle phosphorus from fish sludge, whilst ensuring food chain safety. There are several operators interested in the fish sludge, which today mainly are stakeholders focussing on energy production, e.g. biogas. However, fish sludge well suited for biogas production has significant amount of uneaten fish feed in it. From a fish farming perspective and regarding optimum use of bioresources, it is desirable that the fish sludge consists mainly of faecal matter. It was agreed upon that a unified bio-resource hierarchy is one way forward to achieve this. Such a hierarchy ranks the use of biological residual raw materials, where for example reusage as food is higher in the hierarchy than fuel. On single component level, it was noted that e.g., a phosphorous strategy can be a concrete step to ensure the collection of aquaculture sludge. When it comes to the actual collection , key challenges noted are the lack of proven technologies for fish sludge collection and processing, costs and the need to recover nutrients as marketable products.

Aquaculture feed optimisation

Gregosits Balazs, Vitafort, Hungary, indicated that the company produces precision premixes for intensive livestock feeds, including aquaculture fish feeds. Fish feed formulation is complex because they must be not water soluble, precision pelletised for feed delivery systems, respond to specific fish requirements for growth and health in particular fatty acids and proteins. Vitafort is engaged in research in Europe and implemented complex feeding experiments in Asia to improve feed formulations, including reducing the "feed ratio" (feed input per kg fish), impacts on fish flavour and qualities, improving fish disease resistance.

Fish measuring.

Vegard Øvstetun Flo, Cargill, also emphasised that feed has the most significant environmental impacts of aquaculture. Current standard feed recommendation tables deliver significantly more phosphorus than fish requirements because of the need to ensure adequate supply for all regions and different water temperatures. Fish also intake phosphorus from water (through the gills) but this is small compared to intake from feed.

Feed delivery must take into account availability of phosphorus to the fish. This is considerably lower for plant-based feeds compared to animal-based feeds, and both are lower than for mineral feed additives. Use of phytase coating of fish feed is not effective because of low water temperatures. Phosphorus availability in plant-based feeds can be increased by pre-treatments, for example fermentation. However, the priority for defining feed delivery on fish farms is protein supply, not phosphorus.

The increasing use of plant-based feeds today can in certain case lead to increased use of mineral phosphate additives, but these tend to be soluble, so leading to increased phosphorus losses.

Fish sludge processing technologies

Callum Howard, MRAG, UK, summarised key take-aways of the "Best Available Techniques for Reduction and Reuse of Emissions in Nordic Land-based Aquaculture" (Nordic Council of Ministers 2023). This work showed that there is a wide range of possible processing routes for aquaculture sludge nutrient recycling: pelletisation / input to organic fertiliser production, anaerobic digestion and digestate as fertiliser, pyrolysis to biochar, combustion, use as feedstock for production of algae or insects. Local use as fertiliser with limited processing is often the optimal route, but poses transport, market, and regulatory challenges. Where this is not possible, more advanced processing is needed, due to capital and operational costs this is generally feasible only on larger farms or after pooling waste from multiple farms. Desalinisation of marine sludge can be largely achieved by freshwater filter backwashing. Overall, more demanding BAT requirements for nutrient management tends to push towards larger, more intensive aquaculture farms.

Elin Larsson, EasyMining (Ragn-Sells Group), Sweden, presented EasyMining´s Ash2Phos and Aqua2N technologies, and how these technologies can be used to recover nutrients as phosphorus and nitrogen from fish sludge (for both processes, see ESPP Technology Catalogue). EasyMining is part of the four-year EU project Aquaphoenix funded by Horizon Europe, in which aquaculture waste will be collected from open sea aquaculture pens in Norway and Finland. Sludge collection systems are currently under installation and in the coming years, the sludge will be used to produce biogas, recover phosphorus and nitrogen and cultivate microalgae. The sludge will be filtered in several steps. About 10% dry matter sludge will go to biogas production. After this process, the ammonia in the liquid phase will be recovered with Aqua2N technology, and the solid phase will be incinerated to an ash followed by phosphorus recovery using Ash2Phos technology. Sludge will also be filtered to about 30% dry matter and incinerated without prior biogas production, followed by phosphorus recovery.

Roy Olav Hovlid, Fjell Technology, Norway. The company has developed a range of wastewater treatment systems for aquaculture and fish processing plants. He highlighted the complexity of wastewater treatment in aquaculture with many variables that pose challenges to achieving a stable high capture rate. Among the variables that change the quality of wastewater are: salinity, fish size, type of technology in the fish farming facility, operation regime, temperature, and biomass. The discharge requirements for land-based fish farming facilities are becoming increasingly strict, and Fjell is therefore continuously working to develop its solutions to meet new and more stringent emission permits. This involves biological treatment steps for the removal of nitrogen and BOD, and phosphorus precipitation. The company has different drying technologies that can be dimensioned to any capacity need and combined with patented energy saving process optimisations. Current work includes using synthetic polymer and coagulants with controlled dosage and pH calibration to improve fish sludge solid-liquid separation (for on-land RAS aquaculture systems), achieving up to 93%-95% dry matter and around 90% capture rate of organic material in the wastewater.

Thomas Eilkær, Drying Matter, Denmark, presented the company's sludge water separation and drying solutions, developed for sewage sludges and which can be also used for fish sludges. Mechanical solid-liquid separation generally achieves around 80% dry matter. Many recycling routes require or prefer dry input materials (e.g. pelletisation for organic fertilisers, combustion) so that dried sludge can have a positive market price. Drying Matter's low temperature proprietary belt dryer system can use waste heat (50°C) or closed-cycle heat from heat pumps, to economically dry up to >90% DM. Low temperature operation and belt system design (low crusting) ensure easy operation and low maintenance. ABP Regulation sanitisation parameters (70°C, 1 hour) can be guaranteed.

Paulo Mira Fernandes, NIVA, Norway, cited a Norway Environment Ministry report (6/5/2025) showing that nearly 90% of assessed inland fish farms are not conform to regional discharge limits for nitrogen, phosphorus, organic carbon or suspended solids. A Norway Government Expert Group report (26/5/25) underlines the considerable losses of phosphorus and nitrogen from aquaculture and proposes a tax on fish farms based on these losses.

NIVA notes that new sludge processing technologies are being tested, including:

- Electrodialysis membranes, to separate phosphorus, ammonia, and also address salinity,
- Polyphosphate accumulating microorganisms, similar to EBPR biological P-removal for sewage,
- Use of fish sludge to fertilise biomass production or feed insects, for use as fish feed, with a need to verify biological and contaminant accumulation risks.

He underlines the need to continue looking for new sludge processing technologies and to address nitrogen/ammonia and not only phosphorus.

Biogas from fish sludge and nutrient recycling

Maria Magdalena Estevez Rego, Aquateam COWI, Norway, noted that biogas plant operators in Norway are interested in taking fish sludge as an input material and presented digestion trials carried out with different fish sludges since 2016. Results show that adding fish sludge into anaerobic digesters treating sewage sludge will always increase methane production, but may in some cases reduce methane yield (methane per tonne of input material). Digestate's soluble N and P content is significantly increased. Employing dried fish sludge as co-substrate increases as well the methane production. Fish sludge as a feedstock shows variable nutrient levels with 40-200 gN/kg TS and 10-31 gP/kg TS, and also variable levels of phosphorus availability (7–25% of total-P available as Olsen-P), compared to the available fraction from other feedstocks as 5–7 % in raw chemical P-removal sewage sludge and 30–40 % in raw bio-P sludge). Sludge drying modifies the nutrient availability and leads to loss of soluble fractions and volatile compounds. Nutrients left are not as readily available as in not-dried fish sludge (4% available Olsen-P in dried vs 7–25 % in raw fish sludge) and the overall content of soluble P and soluble N along the AD process is not increased. Addition of dried fish sludge will then increase the methane production and help process stability concerning potential ammonium-N imbalances but produce a digestate with lower soluble nutrients content. Input of fish sludge to sewage sludge digesters results in increased copper and zinc levels in the digestate, in some cases preventing classification as a Norwegian Class 1 and even Class 2 fertiliser of organic origin.

Linn Solli, NIBIO, Norway, also presented studies on anaerobic digestion of both fish sludge and of "fish silage" (unsaleable dead fish and parts of fish from onboard processing brought back to shore by fishing boats). The fish silage materials have high fat and energy content, so significant methane production potential, but also low C/N ratio. For fish sludge, data suggests that the N content is falling somewhat with improved feed use (less uneaten feed in sludge) and ammonia losses in dewatering. Challenges for anaerobic digestion are foaming (which can be addressed by dosing lipids) and salinity. Standard digester microorganisms can normally not tolerate elevated salinity. Recent results show that digesters can adapt to salinity levels equal to sea water (~ 3.5% salt), and such adaptation results in among other factors lower microbial diversity with a few specialists salt-resistant species (which may originate from the sea, via the fish sludge). However, salinity will be an obstacle to digestate valorisation as fertiliser. Zinc levels in fish sludge digestate can also be problematic.

Astrid Nesse, NIBIO, Norway, summarised studies on fish sludge as fertiliser. Pot trials show that phosphorus in fish sludge has around half the short-term plant availability of mineral P fertiliser, and nitrogen short-term availability is also low. The sludge provides organic carbon and can be effectively used in combination with mineral fertiliser. Potassium must also be added. Other challenges to fish sludge use as fertiliser can be metals, as so far there are few studies on the presence of organic contaminants. The sludge must be delivered as a stable, non-smelly material, in a form which farmers can handle with existing farm equipment.

Nazli Pelin Kocatürk Schumacher, NMBU, Norway, presented research from the SEA-CYCLE project, aiming to test different fish sludge treatment techniques, including pyrolysis of raw and digested aquaculture sludge. The investigated factors affecting anaerobic digestion, and preliminary biochemical methane potential tests conducted in 300 ml glass serum bottles for 50 days, show that salinity has a clear negative impact on methane yields during anaerobic digestion. The addition of sorbents (biochar or zeolite) improved performance of biogas production: biochar worked best in freshwater due to its buffering and microbial support properties, while zeolite showed promise in brackish water thanks to its ammonium-binding and ion-exchange capacities. At high salinity, both sorbents mitigated somewhat the inhibition of biogas production. Further experiments are ongoing. She also introduced the ongoing work on feed potential of aquaculture waste and wastewater through microalgae-based approaches. The tested species *(Chlorella vulgaris*, *Nannochloropsis oculata*, *Dunaliella salina*, *Schizoschizochytrium* sp., and *Haematococcus pluvialis)* were evaluated under freshwater and marine conditions. In cultivation experiments using raw effluent directly from fish tanks and filtered, nitrified RAS effluent, the highest growth rates were observed with *Chlorella vulgaris* and *Nannochloropsis oculata*, respectively, corresponding to the fish tank outlet and RAS effluent sources. Aquaculture effluents can be bio-transformed by microalgae into valuable fish feed components, including proteins, carbohydrates, carotenoids, and chlorophyll.

Algae to recycle aquaculture nutrients

Daniel Pleissner, Institut für Lebensmittel und Umweltforschung e.V. (ILU), Germany, explained that microalgae are highly efficient at absorbing phosphorus not taken up by fish in aquaculture (around 80% of the total), making them a promising method for nutrient recovery. In the CLIMAQUA project, *Galdieria sulphuraria* is being cultivated using wastewater from fish processing, dried pellets obtained through fish hydrolysis and fish residues and sludge treatment as well as agricultural residues. Yields of 19–23 g of dry biomass/g ammonium and 76–82 g dry biomass/g phosphate were found. See also Pleissner 2021 DOI and Sloth 2017 DOI.

Riccardo Capolla. STAM, Italy, has developed and tested modular photobioreactors of up to 2000 l volume for wastewater treatment and microalgae cultivation, focusing on nutrient recovery. Designed to be easy to scale up, it produces 0.5 g/l per day of wet biomass. The amount of treated water depends of the kind of wastewater and the nutrients present in it, which may require more than one cycle of treatment to be completely absorbed by the microalgae. CO_2 is fixed from air or flue gas according to specific conditions, allowing for the direct implementation of the system in industrial facilities. Work is ongoing to optimise biomass harvesting to minimise processing losses and to develop a digital system to manage production parameters. Initial testing was carried out in the MOONSHINE project, where algal biomass production was validated using aquaculture wastewater with *Chlorella vulgaris* and *Acutodesmus obliquus*. These strains were then tested as fishmeal substitutes for seabream and trout, showing positive results in terms of growth and immune performance. This system was later integrated and scaled up for hydroponic applications within the PestNu project, where drainage from hydroponic crop cultivation is pretreated and then used to grow microalgae, resulting in both algal biomass and partially treated water. The algal biomass then undergoes enzymatic hydrolysis or biocatalysis to produce a plant growth enhancer, which is reused in the hydroponic system. Finally, in the FRONTSH1P project, it is used to decarbonise hard to abate industries. See also Faliagka 2024, DOI .

Dorinde Kleinegris, NORCE, Norway, presented an ongoing demonstration within the INNOAQUA project, a land-based RAS-IMTA (Recirculating Aquaculture Systems-Integrated Multi-Trophic Aquaculture) coupling salmon and microalgae production (picture below). The pilot test plant in Norway has been operated for several months, where a 25L photobioreactor from NORCE was connected directly to a 2500L RAS module from Marineholmen RASlab, using overflow water from the salmon in freshwater stage, brackish water, and salt water to fertilize microalgae. One challenge of this system is aligning microalgae nutrient requirements with the changing needs of fish at different life stages, including maintaining the correct P:N ratio. Microalgae cultivated in this system removed 80–100% of the nutrients, but further investigation is needed to assess the quality of the algal biomass, particularly concerning bacteria and heavy metal content.

Zhitao Huang, NIVA, Norway, presented the LOCALITY project, which aims to develop algae-based products using side streams from the from the Norwegian aquaculture industry. Different side streams from various fish farm locations and designs (flow-through and RAS) have been collected and characterized for algae cultivation based on their physicochemical properties. Multiple algae species and strains have been screened using these aquaculture side streams, and their growth performance has been monitored. Chlorella *vulgaris* K-1006 has shown particularly promising results and has been selected for further scale-up. The project plans to scale up biomass production in 25L and 1000L reactors. Algae Samples will be analyzed for biochemical composition, including proteins, lipids, and carbohydrates, as well as screened for natural toxins, pesticides, heavy metals, and organic contaminants to evaluate their potential for use in food and feed applications.

Stefan Teerlinck, Inagro, Flanders, (Belgium), explained that aquaponics, a system combining fish and vegetable production in a single-loop setup, requires complex management, cannot fully optimise water quality for both fish and plants simultaneously, and excludes use of pharmaceuticals for the fish. To partly overcome these limits, decoupled systems separate fish and vegetable production but are connected by shared rainwater resources and infrastructure with f ish effluent directed to the greenhouse as a function of water and nutrient requirements and quality parameters. Trials growing tomatoes in such systems operated for one growing seasons, showed yields and blossom end rot comparable to standard methods. Challenges include managing fish disease and sodium levels.

Carlos Octavio Letelier-Gordo, DTU, Denmark, presented strategies for the valorisation of freshwater and marine recirculating aquaculture system (RAS) effluents. The RAS overflow (75% of total flow) contains higher concentrations of nitrogen, while the sludge flow (25%) contains suspended solids, phosphorus, organic matter and micronutrients. Several valorisation options for sludge flow were discussed: biogas production; fish manure cakes (these can be produced to remove carbon, phosphorus, and nitrogen, and typically contain small amounts of heavy metals, and can be tailored with added compounds depending on their intended application (e.g., as fertiliser or for biogas production); seaweed and biomass cultivation.

Siri Caspersen, SLU, Sweden, presented results from the Nutribatt project, which explored at lab scale the potential of nutrient-loaded biochar from RAS as a fertiliser and growing substrate component. Wood biochar was placed in RAS systems to absorb nutrients, and then used in plant cultivation experiments. The RAS-loaded biochar showed increased concentrations of NO_3-N, S, P, Na, Al, Cu, Zn, and Si, while levels of K, Mg, EC, and pH decreased. Pot experiments with sunflowers demonstrated a positive effect on plant growth when using the nutrient-loaded biochar. Compared to unloaded biochar, the RAS-treated material was significantly more effective as a fertiliser, mainly due to changes in pH and nutrient availability. The addition of peat further improved the availability of phosphorus and aluminium showing the significance of interactions with other substrate components. See also Behjat 2025 DOI.

Life Cycle Analysis studies

Kari-Anne Lyng, NORSUS, Norway. Within the Circulizer project, an LCA will be conducted to compare aquaculture waste management options (fish sludge, fish silage). Preliminary results show that outcomes depend on multiple factors such as nitrogen and phosphorus content in the sludge or silage, transport distances and fuel types, collection methods, and biogas potential.

Hanna Böpple, NORCE, Norway, presented LCA research from the SLAM-DUNK project, assessing different scenarios for treating aquaculture waste streams (fish sludge and nutrient-rich wastewater) from an RAS facility in Norway. Transport of the dewatered fish sludge to Denmark then anaerobic digestion, and local discharge of the reject water was compared to local use for anaerobic digestion connected to microalgae cultivation on the reject water and digestate. The LCA suggested that the local use scenario was preferable. Geographical differences in electricity sources between Norway and Denmark had a significant influence on LCA conclusions. Transport of sludge to Denmark contributed minimally to total impacts. See also Böpple 2025 DOI.

Jean-François Fabre, Institut National Polytechnique de Toulouse, France, presented sustainability assessment of bio-based fertilisers obtained from fish and aquaculture by-products as part of the SEA2LAND project (EU Horizon 2020). A case study using trout heads and bones applies thermo-mechano-chemical fractionation via twin-screw extrusion to produce solid and liquid fertilisers plus fish oil. Life cycle assessment, life cycle costing and social life cycle revealed a major hotspot in the drying phase, notably due to high energy input and a large number of working hours with risks of injury. Synergies can be found between environmental, social and economic aspects, such as the limited use of chemicals (lower toxicity for ecosystems, lower process costs, reduced health and safety risks, respectively).

Research

Simona Paolacci, AquaBioTech Group, Malta, summarised key conclusions from a number of R&D projects addressing aquaculture sustainability:

- The highest LCA impact of fish farming is from feed production.
- Replacing animal-based feed by plant-, algae- or insect-based feed offers LCA benefits, but shows varying impacts on production for different fish species.
- There is still potential to increase use of fisheries by-products in aquaculture feed, for example low-value fish species which are today discarded back to the sea in order to avoid their being counted in fishing 'quotas'.
- Feed wastage is significant, with uneaten feed ending up in fish sludge. Automated monitoring and control systems can reduce feed losses, for example cameras monitoring fish in cages with appropriate software can identify from fish swimming behaviour whether they are hungry and can estimate fish weights to adjust feed supply.
- Analysis of fish bones can indicate whether nutrients in feed are adequate or are being taken up.
- Studies on biological safety and contaminants (e.g. heavy metals) in alternative or recycled feeds are important.

Lucia Drábiková, Institute of Marine Research Norway, presented results of a recently published research into impacts of diets with phosphorus levels higher and lower than standard recommendations on the bone health (vertebral deformities, bone strength, and bone mineralisation) of farmed Atlantic salmon (1.8-4.5 kg) (Drábiková et al., 2026). Results showed the need to adjust diets according to the season and fish life stage. The currently used level of dietary phosphorus (5.8 g available phosphorus /kg) in the on-growing phase of salmon falls above the requirements of the species. The study showed that by targeting the updated requirements (3.7-4.6 g/kg), it is possible to reduce the use of inorganic phosphorus by 16-24%. The application of the newly established recommendations would improve management of the limited and expensive resource that inorganic phosphorus represents. Optimised levels of dietary phosphorus enhanced its utilisation (digestibility and retention) in animals and reduced dissolved phosphorus excretion by up to 37% during the final six months of the production cycle.

Turid Synnøve Aas, Nofima (Norway), indicated that nearly 40% of fish feed phosphorus was not used by fish in typical land-based salmon farm, calculated from mass balance. She estimated that around 2/3 of the phosphorus in feed was taken up by fish (i.e. feed eaten and phosphorus transferred to bloodstream), of which around half was transferred to fish flesh development and around half was re-excreted in metabolism (in soluble form from fish kidneys). Salmon efficiently digest fat and protein, but only poorly carbohydrate and minerals. The remaining 1/3 was in fish sludge (uneaten feed plus faeces). Current marine systems may collect only around 1/3 of this sludge. Uneaten feed is easier to collect than fish faeces, so levels of feed in sludge may be unrepresentatively high. Modelling suggests that 0.9 – 2.7 kgP (phosphorus) can be collected in sludge per tonne salmon produced, with 1.3 - 1.9 %P/DM in collected sludge. The modelling showed how concentrations of zinc and cadmium in sludge increased if there is no feed in the sludge (16 – 38 gZn and 0.2 – 0.5 mgCd per tonne salmon produced).

Site visit

Participants visited an **in-sea salmon farm with an innovative fish sludge collection system.**

The collected fish sludge consists of fish faeces, uneaten feed, but also leaves and dead fish. The sludge is collected by pumps from by a fine-gauge net system below the floating fish enclosures, then undergoes mechanical solid-liquid separation, to sludge and discharge water returned to the sea. Collection of the sludge reduces nutrient and organic inputs into the fjord, so reducing eutrophication risk, and enables energy and nutrient valorisation from the sludge by RagnSells by anaerobic digestion.

Workshop key messages

from the uPcycle workshop on Phosphorus Sustainability in Aquaculture, Bergen, June 2025

The workshop finished with a 'post-it' session for Bergen and online participants. Based on this input, and after consultation of workshop speakers and participants, the workshop's key messages and input to the UNEP uPcycle White Paper are:

- **Aquaculture feed is the most important sustainability factor for aquaculture**, as shown by LCAs. This concerns feed production (e.g. origin of protein: animal or vegetable, primary or secondary), efficiency of feed delivery (reducing feed loss) and feed digestibility. Feed loss results in both feed wastage and nutrient pollution.
- **Nutrient loss reduction** is an increasing priority, to respect EU Water Framework Directive and other water policy objectives, and to achieve the UN Kunming / EU Green Deal target to reduce nutrient losses by -50%.
- **Difficulties of geography**: marine aquaculture is often situated in regions with little agricultural demand for fertilisers (an obstacle to local nutrient recycling of aquaculture sludge), disconnect from infrastructure, difficulties for skilled recruitment. This is true both in Northern Coastal regions (Norway, Scotland, Ireland …) but also on the Mediterranean coast (2 million tonnes/year of aquaculture fish production in the Mediterranean, not including shellfish …). Different solutions are appropriate to different local situations and economic realities.
- **Importance of dialogue** between the aquaculture industry, policy makers, research experts on technologies and roll-out, nutrient management priorities, regulation, research needs …
- **Regulatory challenges In Europe**: barriers to nutrient recycling from aquaculture wastes in EU Regulations should be addressed (including Animal B- Products and Fertilising Products regulations. There is a need for dialogue to clearly identify regulatory barriers and uncertainties and propose safe and sustainable solutions.
- **EFSA (European Food Safety Agency):** In particular, it should be defined what questions could be put to EFSA on safety of fish sludge nutrient valorisation (what uses, input sludge specifications, processing conditions, contaminant limits, other conditions) and consequently to collate and where necessary develop data to support the defined questions to EFSA.
- **Policies should consider full value-chain LCA**. Aquaculture sludge contains significant phosphorus and nitrogen and also organic carbon. Reducing nutrient losses (water quality – eutrophication) is a key driver. Vigilance is needed to avoid pernicious side-effects of policies (e.g. over-feeding to increase feed content of sludge to enhance nutrient value for recycling)
- **Further research is needed**:
  - biological safety of fish and aquaculture sludges for use as fertiliser,
  - contaminants in aquaculture sludges: zinc, copper, iron, heavy metals, fish pharmaceuticals, bioaccumulative organic micropollutants,
  - salinity in marine aquaculture sludge / digestate and salinity-reduction processes,
  - impacts of salinity of aquaculture wastes on biogas production in AD processes and routes to mitigate this (digestion additives, microbial selection …)
  - development and full-scale technology testing of fish sludge collection, handling and storage (including H2S avoidance), concentration and drying, transport and logistics, processing and nutrient recovery,
  - use of algae to treat aquaculture sludges and wastewaters and safety, quality and potential uses of produced biomass (contaminants, nutrient availability …)
  - feeds and feed delivery to improve sludge collectability,
  - feed use efficiency: digestibility (particularly of plant-based feeds), non-invasive methods to optimise fish feed composition and on-farm delivery (without killing fish for bone analysis), real-time automated systems to adjust feed delivery rate to requirements (fish size, behaviour, water temperature …)
  - large variation in fish sludge, and underlying causes are poorly understood
- **Fish farmers are key.** Fish sludge collection, handling and nutrient recycling solutions must be economic and feasible on-farm. Information, training and motivation of fish farmers are essential.
- **Valorise nutrient stewardship in the market** and ensure fair competition in the global aquaculture products market. How to enable farmers and seafood companies to valorise nutrient sustainability in product labels or other market tools ?

European Wastewater Management Conference

Europe's leading wastewater industry conference, 19th EWWMC (AquaEnviro) showcased operational experience and practical solutions, with sessions on phosphorus, circular economy, micropollutants & PFAS, nature-based solutions. The conference, held in Telford, 1960's new town in the centre of England, attracted over 400 participants from nearly 200 water treatment and supplier companies, from 20 countries worldwide.

The conference addressed water treatment process intensification, climate emissions reductions (in particular N_2O), removal of micropollutants and PFAS, asset management and investment, CSOs and stormwater, nature-based solutions and included a detailed session on phosphorus removal. This session looked at operating experience of technologies for achieving low phosphorus discharge consents (0.5 – 0.1 mgP/l), in particular in smaller waste water treatment plants (wwtps) and with optimisation of existing assets. **The text below summarises this phosphorus session only:** there was lots more conference content which is not summarised below, sorry!

19th European Wastewater Management Conference & Exhibition (EWWMC), Telford UK, 17-18 June 2025, https://ewwmconference.com
30th European Biosolids & Bioresources Conference (AquaEnviro), 11-12 November, Manchester, UK https://european-biosolids.com/2025
20th European Wastewater Management Conference, 16-17 June 2026, Telford International Centre, UK https://ewwmconference.com


ESPP presented the important new obligations for nutrient removal and phosphorus reuse & recycling of the recast EU Urban Waste Water Treatment Directive 2024/3019. ESPP conference presentations are here: https://www.slideshare.net/phosphorusplatform

Jo Jolly, OFWAT (UK water industry regulator) underlined the contribution of waste water treatment innovation to the planet's future, in particular climate change and biodiversity.

UK wastewater treatment funding for 2025-2030 (AMP8) includes a significant allocation for nature-based solutions. For example, restoring seagrass in estuaries can contribute economically to P and N sequestration, in synergy with habitat restoration.

Tertiary fine solids removal for low P discharge

Callum Grundy, United Utilities, and Brian Jones, Veolia Water Technologies, presented experience using the natural coagulant Hydrex™ 62925 (a renewable plant-based coagulant produced from tree bark, authorised for use in food and beverage industry) to improve P and iron removal, by improving settling of iron phosphate flocs. United Utilities was the lead partner in a nationwide project to put alternative methods of phosphorus removal to the test. Backed by Ofwat's Water Breakthrough Challenge, researchers examined a range of methods, including the use of natural coagulants. Following a successful six-month on-site trial in a test lane at their Woolton wwtp, Merseyside, UK, United Utilities has deployed the technology as the permanent solution at Madely wwtp (6 000 p.e.), combined with iron dosing, achieving < 0.25 mgP_{total}/l discharge. This is now a standardised solution for United Utilities as part the AMP8 capital programme and has been rolled out operationally, to achieve demanding P discharge consents. To date, there have been ten deployments across United Utilities. A key benefit is that the tannins present in the natural coagulant work to reduce residual iron, so reducing iron levels in discharge and potentially avoiding requirements for additional solids removal.

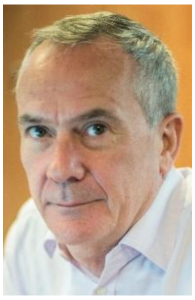
Mathijs Oosterhuis, Haskoning, and Pim de Jager, Aquacare Europe, updated on the BIOPHree® technology (see SCOPE Newsletters n°156, n°138 and n°132) to achieve low P discharge using beds of iron oxide granules to treat final effluent, after filtration (that is, installation downstream of systems such as cloth filters or sand filters). A contact time of 5 minutes enables reduction from 1 to < 0.1 mgP_{total}/l discharge and also removal of organics (humic substances). The iron oxide granules can be regenerated using NaOH, followed by a nanofiltration membrane, to recover NaOH (70-90% recovery achieved), separate organics and generate a P-solution for P-recovery: a phosphate solution 2 000 – 3 000 mgP/l representing c. 10 % of wwtp P inflow (depending on the pre-existing P-removal in the wwtp, this fraction can be higher). The process has been tested at 3 m^3/h scale for fifteen months at Dronten wwtp The Netherlands, showing effectiveness of the iron oxide granule regeneration (6 regenerations, average 2 500 bed volumes treated per regeneration). Haskoning and Aquacare are preparing for a first demonstration scale installation (circa 100 m^3/hr) at a Water Authority in the Netherlands as a follow-up from this pilot study. *Photo: BIOPHree® 3 m^3/h pilot.*

Connor Sandalls, Southern Water UK, presented N and P removal in denitrifying sand fillers. Southern Water currently has total N discharge limits of 15 mgN/l or lower for 12 wwtps and expects implementation of total N consents at a further 25 wwtps in the coming five years (AMP8), with total N limits coming down to 9 – 10 mgTN/l. An example is Bishops Waltham wwtp (15 000 p.e.), a trickling filter plant, which currently has a 15 mgN/l discharge consent and will now also have a 0.4 mgP/l consent. The site currently uses denitrifying sand filters and humus tanks, and a concern is whether this is compatible with low P, achieved by ferric dosing, because P is needed to feed the denitrification process. Results confirm that very low P does impact denitrification, but that P-removal down to 0.15 mgP/l can be achieved compatible with maintaining denitrification. Ferric dosing point and control were critical to performance.

Thomas Fundneider from Mecana, in co-presentation with **ELIQUO**, presented approaches for meeting stringent effluent consent limits for total phosphorus by dosing iron or aluminium coagulants followed by filtration using OptiFiber® Pile Cloth Media Filters (PCMF®). This process enables the removal of nearly all precipitated phosphate particles. Correct dosing and thorough mixing of the coagulant are essential for achieving very low effluent concentrations. Different PCMF configurations are available: drum filters or pressure drum filters are suitable for small flow rates, while disk filters are used for higher flow rates. These filters can be equipped with various Pile Cloth Media types, including Micro- and Ultrafiber, as well as suction lips (like OptiComb®) to allow optimal adaptation to both process requirements and media characteristics. Currently, several

Photos: Neumünster wwtp, Germany, Walsall Wood wwtp, UK.

hundred Mecana PCMF units are in full-scale operation at municipal and industrial wastewater treatment plants across Europe (see SCOPE Newsletter n°129), consistently achieving total phosphorus effluent concentrations as low as 0.2 mgP/l. An additional synergistic effect of phosphorus removal using PCMF is the retention of fine organic particles, which leads to reduced effluent COD and BOD concentrations. Furthermore, microplastics in the wastewater treatment plant effluent can be reduced by more than 95 %.

Callum Grundy, United Utilities, and **Andrew Baird, WCS Environment. Engineering,** presented the Flocell XFM modular filtration tertiary solids removal system. The system is adapted from use in decorative Koi carp water treatment (one such carp was sold at auction for over £1 million, so the filter system is robust and highly efficient). The system uses an open-cell HDPE (high density polyethylene) filter media. The open cell media means that there is no head loss: if it reaches maximum solids retention, rather than blocking and bypassing, there is no hydraulic restriction and flow will continue to pass through the filter (but without further solids removal). The units are sized for a periodic scour cycle to remove solids, generally designed to be undertaken every 2 weeks, however a proactive weekly clean is advised. The system is delivered in 5 l/s modules, scalable by installing units in parallel to meet varying flow requirements—up to 40 l/s per system. Units are fully containerised and modular, making deployment flexible and efficient. Testing of the Flocell XFM technology by United Utilities for three months at Appleby wwtp (c. 4 500 p.e.) concluded successful P-removal to the target of 0.25 mgP_{total}/l, when combined with ferric dosing. TSS < 10 mg/l was also achieved. Through extensive testing, optimal performance was achieved when operated in dialysis mode.

At the end of this trial, United Utilities retained the unit and multiple others have been deployed into operation. The technology is now progressing through an internal design process to standardise the unit for other sites where TSS and P-removal are being considered. *Photo: Flocell XFM installation for trial at Appleby wwtp, United Utilities.*

Cost-effective P discharge reduction with existing assets

Philani Nube and Danmore Juru, Severn Trent Water UK, presented experience of advanced P-removal technologies in the company's wwtps. Biological phosphorus removal (EBPR) generally offers better whole life cost and avoids reliance on chemical coagulants, but often cannot robustly achieve P discharge consents of 0.5 mgP/l or lower. For example, optimisation of EBPR by using fermentation of sewage sludge to release readily available carbon to 'feed' the EBPR biology, at Loughborough wwtp (73 000 p.e.), Pinxton wwtp (10 000 p.e.), and Grendon wwtp (6 800 p.e.), showed that P discharge could be reduced to maybe average 0.6 mgP_{-total}/l but with significant variations. Conclusions are that appropriately managed sludge fermenters (or return activated sludge RAS and/or denitrified mixed liquor DNML) can improve EBPR performance, but this may not be sufficient to reliably achieve low P discharge consents (< 0.5 mgP/l) without some chemical coagulant dosing.

Neil Campbell, Morgan Sindall, presented holistic action to reduce P loads to the River Wye (Wales and England). Of the current total P load, around ¾ is from agriculture and ¼ from sewage works. The environment regulator is requiring a 75% reduction in wwtp P-discharges to the catchment from 2025-2027 (AMPs 7 and 8), requiring action at 18 wwtps. To achieve this, different processes were assessed, including chemical coagulant dosing, alkalinity dosing, optimisation of existing clarification and addition of tertiary solids removal (multi-media or sand filters), to remove fine precipitated phosphate particles. To achieve <0.5 mgP/l, the combination of all three were necessary and Bluewater Bio FilterClear (SCOPE Newsletter n°125) or Brightwork Continuous Sand Filters (SCOPE Newsletter n°141) were used for tertiary solids removal. These systems achieved 0.23 – 0.3 mgP/ discharge as well as significantly reducing ammonia. *Photos: Leominster wwtp Brightworks Moving Bed Nitrifying Sand Filter, Rotherwas Hereford wwtp Bluewater Bio TSR plant.*


Jeremy Biddle, Bluewater Bio and **Silas Warren, Wessex Water**, summarised a collaborative project to standardise the design of both the FilterClear Multimedia Filter (MMF) plants and also the associated civil, mechanical and electrical works. Wessex Water are installing the MMF systems (see SCOPE Newsletter n°149, EWWMC 2023) to achieve low phosphorus discharge consents, down to 0.5 – 0.1 mgP_{total}/l. The standardised design will reduce the cost and time involved compared with the traditional approach of bespoke designs for every site, even if the equipment is standard. Wessex Water had successfully applied this approach in AMP7 for ferric dosing plants. Standardisation of MMF designs is predicted to yield cost savings of 20-40% as well as programme and resourcing savings. The utility currently faces tightening of P discharge consents for one hundred wwtps, mostly small wwtps. Bluewater Bio has developed a range of adaptable modular MMF plants. These are pre-wired and skid-mounted, produced by a number of different manufacturers using standardised equipment. The reduced range of adaptable plants enables Wessex Water to make early decisions about procurement, even before their engineering teams have completed outline designs. Advanced procurement enables the supply chain to utilise available manufacturing capacity at the start of the AMP cycle, reducing prices and inflation risks to water company clients as well as providing certainty that the MMF plant will be ready to meet project programmes. *Photo: BlueWater Bio FilterClear Multimedia Filter providing tertiary P-removal at Rowde wwtp, Wessex Water (6 000 p.e.).*

Shaun Stevens, EPS Water, discussed optimisation of final solids settling tanks, which exist in nearly all wwtps, and where performance of solids settling is key to reducing discharge BOD, TSS and phosphorus. Despite technologies to reduce turbulence, such as baffles, design is never adapted to varying flow conditions. Adaptive inlets systems ensure vary input height and configuration depending on flow, with wide opening high in the tank (into the sludge blanket) in high flow conditions, and narrow opening below the clear water interface at low flows. This can be optimised by control systems linked to sludge blanket and discharge TSS monitors. Over 100 operating sites worldwide show and increase in settling tank capacity by +30% for the same discharge quality and can achieve < 0.5 mgP_{-total}/l. *Photo: EPSWater Hydrograv Adapt installed at Nansemond wwtp, Virginia, USA.*

Innovative P-removal technologies

Tomasz Skonieczny, Veolia Water Technologies, presented the company's new Cella™ development on MBBR (Moving Bed Biofilm Reactor) technologies. Cella combines compact BOD, N and P biological removal, and yields increased methane recovery potential from the output sludge. A new bio-based support material (AnoxKTM C), 0.7 – 4.5 mm, produced from recycled biomass, is combined with a new configuration design and operation based on alternating feed direction in two main reactor compartments equipped with energy-efficient internals (separator, mixer, fine bubble aeration). The technology for C and N removal (Cella CN) is currently under first year operation in Denmark, at Svinninge Holbaek wwtp, as a sidestream addition to the existing plant, enabling an increase in capacity from 4 000 to 6 000 p.e. Optimisation aims to achieve overall plant effluent discharge down to < 8 mgTIN/l. Phosphorus removal has been tested in separate studies at different locations achieving P_{-PO4}<0.5mg/l. *Photo: Veolia Cella CN at Svinninge wwtp Denmark.*

Frederico Pesci, Power & Water, presented experience combining electrocoagulation and natural coagulants (tannin). Electrocoagulation uses a sacrificial anode under electrical current to release either iron or aluminium to remove phosphorus. Power & Water's Soneco® technology uses ultrasound to avoid electrode passivation, so reducing maintenance downtime (see detail in [ESPP SCOPE Newsletter n°149](), summary of EWWMC 2023). Benefits include avoiding chemical coagulant handling challenges and no pH change. Soneco installations are today operational in the UK, Europe, Canada and Singapore. Electrocoagulation was combined with natural coagulants to improve P removal without using polymer coagulants, using lamella tanks for settling. Testing full scale at the United Utilities Woolton UK wwtp, treating 2 m^3/hour for 6 months, showed good energy efficiency and reduction of effluent P below 0.5 mgP-$_{total}$/l with low effluent iron concentrations. Trials at other wwtps (400 – 1000 p.e.) confirmed these results.

Photos: Soneco units operating at sewage works.

Rebecca Shields-Smith, United Utilities and Neil Townend, Haskoning, presented full scale operation of the Nereda P-removal process (aerobic granulated sludge biological P-removal, see [SCOPE Newsletter n°133]()), combined with ferric dosing, at the Failsworth (Manchester) wwtp (23 000 p.e.). Nereda treats crude wastewater, replacing

the previous trickling filters and nitrifying trickling filters. This trialled single-point input (crude wastewater) ferric dosing with the aim of achieving 0.3 mgTP/l discharge consents. Full-scale operating results show that with reduced ferric dosing, <0.25 mgP/ was achieved, with significant operating cost savings (reduced chemical dosing) and CAPEX savings (no need for tertiary solids removal). Some challenges were identified in managing storm and dry-weather flows (an effluent buffer tank is needed) and reduced sludge thickness (changing polymer dosing is under investigation). The Nereda unit does however provide resilience to the overall wwtp system, offering a capacity to deal with temporary changes in influent in a single treatment stage, whilst meeting low phosphorus discharge limits without the need for tertiary dosing/solids removal. *Photo: Nereda unit at Failsworth wwtp (United Utilities, UK).*

Callum Grundy, United Utilities and Michelle Marriott, Haigh Group, presented FujiClean, a modular Japanese technology, which offers chemical-free phosphorous removal combined with standard biological treatment for small-scale wwtps, as well as opportunity for upgrading septic tank systems. The P-removal is based on biological processes combined with electrocoagulation: the system contains a sedimentation chamber, an anaerobic zone, and an aerobic zone resulting in P-removal, settling of precipitated phosphorus and BOD, fluidised-bed bio-film filtration for ammonia removal with very low sludge generation. There are over 2 million FujiClean units deployed across Japan, the US and Australia with 200 systems operational in the UK for small rural populations, private homes, farms and small commercial sites. The system is ideal for up to 50 to 100 p.e. per unit, depending on treatment requirements. Units can be deployed using a modular approach for larger populations.

United Utilities has conducted an extensive trial of the FujiClean technology and, following this trial's success, became the first water company in Europe to adopt the technology, via a partnership with Haigh Environmental, who hold the exclusive UK license for this product. The technology is now operational at sites in Shropshire and Cheshire. Notably, this marks the first known use of the system on municipal wastewater in Europe. FujiClean has now been adopted as one of United Utilities' standard phosphorus removal solutions for AMP8. *Photo: FujiClean unit installation at Whitegate wwtp, United Utilities.*

Ania Escudero, Glasgow Caledonian University, presented the Scottish Hydro Nation Chair research & innovation programme and work on phosphorus recovery from wastewater, building on the Phos4You EU Interreg project (2017-2021, see SCOPE Newsletter n°141). Research trials at the Wastewater Development Centre in Bo'ness showed that

microalgae (*Chlamydomonas acidophila*) in contained systems can robustly achieve 50-75% phosphate removal, 75-100% ammonia removal and 50% COD reduction. The recovered microalgal biomass met EU Fertilising Products Regulation limits for contaminants and pathogens, except for copper (520 mg kg^{-1}). Since the end of Phos4You in 2021, the Hydro Nation Chair team is supporting and facilitating phosphorus recovery technology trials (such as P-adsorption, microalgae, hydrothermal carbonisation) and developing projects focused on market opportunities for recovered P products, with the aim of accelerating deployment of circular solutions in Scotland.

Ayisha Affo Souleymane, Cranfield University, summarised research into phosphorus removal in around forty artificial wetlands, looking at P mechanisms in the water column, detritus layer, sediments and vegetation. Average discharge from such wetlands was c. 3 mgP/l, and wetlands achieved < 1 mgP/l only when inflow was already < 3 mgP/l. P-removal performance varied widely over different seasons of the year. Overall, the systems operate stably for up to 30 years. Around 10% of P uptake is in plants, 70% to sediment and 20% remains not identified. A loading rage of 30 – 50 mgP/m^3/year is needed to achieve 1 mgP/l discharge.

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