BALTIC RIM ECONOMIES

Sustainable Nutrient Management

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ERIK SINDHØJ & CHERYL MARIE CORDEIRO

Circular economy for nutrients in the Baltic Sea Region

Expert article • 3781

Background

Nutrient losses from agriculture drive eutrophication in the Baltic Sea. To address this, the Baltic Sea Regional Nutrient Recycling Strategy (BSR NRS) and the EU Strategy for the Baltic Sea Region (EUSBSR) Policy Area (PA) Nutri provide a framework for minimizing nutrient losses and promoting circular nutrient use through enhancing nutrient recycling. PA Nutri plays a key role in coordinating regional cooperation and aligning policies to support transnational nutrient management efforts.

However, despite policy commitments, the transition to circular nutrient solutions faces significant challenges, including technological, economic and regulatory barriers. The CiNURGi project, funded by Interreg BSR (#C049), directly supports BSR NRS and PA Nutri by addressing these challenges through a cross sectoral approach, linking agriculture, municipal, and industrial nutrient recycling solutions to promote regional circular nutrient management. This article explores CiNURGi's approach to addressing these challenges to advance nutrient recycling in the BSR.

Challenges in scaling up nutrient recycling

Despite their benefits, Recycled Nutrient Fertilizers (RNFs) face technical, logistical, economic, and regulatory hurdles. Unlike cheap, consistent, and easy-to-use mineral fertilizers, RNFs often have higher costs, quality variability, and infrastructure limitations. CiNURGi facilitates transnational collaboration, bringing together partners across the BSR to support nutrient reallocation strategies and RNF adoption.

Technological challenges

Advancing nutrient recovery technologies is essential for making RNFs more viable. While methods such as struvite precipitation, biochar production, and anaerobic digestion (AD) have improved nutrient recycling, they still face high costs, energy demands, and efficiency limitations. Struvite precipitation efficiently extract phosphorus, but contaminant risks and chemical input costs can hinder large-scale implementation. Biochar production recovers phosphorus and potassium but lacks efficient nitrogen capture, and uncertainties remain about nutrient availability in biochar. AD is widely used for manure and food waste streams, yet high transportation and management costs limit the recycling potential of nutrients in digestate.

To address these limitations, CiNURGi is piloting phosphorus-rich fertilizers from incinerated biomass, source-separated dried urine fertilizers, and precision agriculture technologies for better nutrient-use efficiency. By implementing pilot investments, CiNURGi demonstrates scalable solutions to enhance the efficiency, cost-effectiveness, and quality of RNFs. In addition, CiNURGi has established Technology Support Centers to help match processing technologies with nutrient-rich biomass streams and secondary raw materials, supporting farmers, SMEs, and policymakers in adopting tailored nutrient recycling solutions. The project also highlights successful case studies of RNF production across the BSR.

Contaminants and safety concerns, agronomic reliability

Ensuring safe and reliable RNFs is critical. Depending on the feedstock and processing method, RNFs may contain heavy metals, organic pollutants, pathogens, or microplastics. Emerging contaminants, such as antibiotic resistance genes and microplastics, require ongoing research and monitoring to mitigate environmental and health risks. Regulatory frameworks must balance safety and innovation, ensuring strict safety standards do not stifle progress in nutrient recycling technologies.

To address these concerns, CiNURGi is developing industry safety guidelines and pollutant monitoring protocols, ensuring RNFs meet quality standards for agricultural use. Through comprehensive assessments of pollutant levels in different waste streams, the project identifies risks and determines best practices for processing. CiNURGi is also working on regional safety requirements to align RNF production with EU fertilizer regulations while allowing room for technological innovation.

Agronomic performance is another key concern. Farmers may hesitate to adopt RNFs due to variability in nutrient content and availability, which can impact crop yields and profitability. Unlike synthetic fertilizers with precise formulations, RNFs vary depending on feedstock composition and processing techniques. To improve confidence in RNFs, CiNURGi has established Evaluation Centers to test draft industry standards and assess the agronomic potential of these products.

Spatial and logistical barriers

One of the biggest challenges in nutrient recycling is the geographic mismatch between nutrient surplus regions, often livestock-intensive areas, and nutrient-deficit regions, where crops require fertilization. Transporting bulky, low-nutrient-density materials such as manure, digestate, or sludge over long distances is costly and inefficient.

To address this, CiNURGi is mapping biomass streams to identify nutrient hotspots and determine regional nutrient deficits, enabling more efficient redistribution strategies. This ensures that nutrients reach the areas where they are most needed, reducing waste and improving circular nutrient flows.

Economic barriers

The high cost of RNFs is a major hurdle to farmer adoption. While mineral fertilizers remain the cheaper and more convenient option, RNFs often have high processing, production, and transportation costs. Without market support mechanisms or financial incentives, RNFs struggle to compete with synthetic fertilizers.

Regulatory and policy challenges

Regulatory frameworks play a crucial role in shaping the RNF market, but current policies often lack flexibility or create barriers to adoption. Strict EU contaminant regulations, while essential for environmental protection, can limit innovation in nutrient recycling technologies. At the same time, there are few incentives for farmers to switch to RNFs, slowing market development. To scale up RNF adoption, policies must provide financial incentives, such as subsidies, tax reductions, and certification programs to support both RNF producers and farmers. Regulations should also facilitate nutrient redistribution, allowing nutrients from surplus livestock regions to be transported to deficit crop production areas more efficiently.

Moving forward

Overcoming these challenges requires technological advancements, improved logistics, stronger regulatory frameworks, and financial incentives to support nutrient recycling. A key factor in scaling up RNF adoption is market demand—without a strong market pull, production will remain limited. Farmers and the food industry need clear economic incentives to choose RNFs over conventional fertilizers. Policies should stimulate demand through subsidies, tax incentives, and procurement programs, making RNFs a financially viable alternative. Additionally, certification schemes and guaranteed markets—such as public sector commitments to purchase RNFs—can help build confidence and long-term investment in the sector.

The EUSBSR PA Nutri plays a critical role in ensuring that nutrient recycling remains a transnational priority. Through its coordination efforts, PA Nutri fosters policy alignment, promotes best practices, and facilitates cooperation among countries to stay focused on the goal of increasing circularity with nutrients. Continued support for PA Nutri is essential to ensuring regional consistency in nutrient recycling strategies, strengthening policy incentives, and driving investments in circular nutrient solutions.

Achieving a circular nutrient economy will depend largely on policy frameworks that not only promotes RNF production but also create a stable and growing market for these products. If demand is established, production will follow, driving further innovation and cost reductions. With the right policy coordination, financial incentives, and cross-sector collaboration, RNFs can become a competitive and trusted alternative in modern agriculture, helping close nutrient loops and reduce agricultures environmental impact across the Baltic Sea Region.

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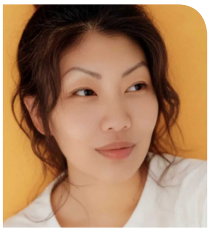

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Circular economy research in the Baltic Sea Region

Expert article • 3782

Almost two decades ago, in 2007, the Baltic Rim countries came together to set up the Baltic Sea Action Plan, aiming to improve the strong eutrophication of the Baltic Sea and the poor condition of the surface waters transporting excess nutrients from the Baltic Rim countries into it. Nutrient losses from agriculture were identified as one of the major causes of eutrophication. With the Baltic Sea Action Plan, a series of **agricultural research projects** was initiated with the major target to systematically develop sustainable nutrient management strategies for the Baltic Sea Region (BSR), to reduce environmental impacts, optimise resource use and move towards a circular bio-economy. From the start, Germany, represented by its Federal Research Centre for Cultivated Plants, was part of this process.

EcoRegion (2009-2012) was the first large scale research initiative emphasising the need for circular nutrient management in the BSR. The main objective of EcoRegion was to support the realisation of sustainable development practices in the BSR. To do so, different Best Management Practices from different sectors were collected and major obstacles for a sustainable development identified. With view to agriculture, focus was placed on collecting good agricultural practices minimising negative environmental impacts of food and feed production. Since immoderate manure applications were identified as major reasons for nutrients loss (especially of nitrogen [N] and phosphorus [P]) from agro-ecosystems into water bodies, causing the regular eutrophication of the Baltic Sea, practices aiming to reduce nutrient loss were of major interest. Among the strategies were improved manure handling techniques, the establishment of buffer zones and constructed wetlands to capture excess nutrients before they reach waterways, and optimised practices for balanced fertilisation. Based on these findings, policy recommendations to increase the sustainability of agricultural activities were formulated. EcoRegion brought together scientists, policy makers and farmers to discuss sustainable agricultural development. This multi stakeholder collaboration resulted in networks that would later facilitate the implementation of targeted nutrient reduction strategies across the region. EcoRegion was crucial in highlighting the urgent need for changes in agricultural practices, particularly in relation to manure management.

Baltic Manure (2010-2013) marked *a paradigm shift in the perception of manure, transforming it from an environmental problem to a valuable resource for both nutrient recycling and bioenergy production.* Until then, manure was often simply disposed of on agricultural land, leading to poor management practices resulting in nutrient loss, excessive emissions and pollution. Baltic Manure demonstrated the economic value of manure by exploring its potential for nutrient recovery and use in bioenergy production. A key aspect was the identification and evaluation of *manure treatment technologies,* including mechanical separation, biogas production and phosphorus extraction methods. These technologies were tested for their efficiency, environmental impact and economic feasibility. The project also developed *business models for manure-based bioenergy and fertiliser production,* demonstrating the potential for profitable nutrient recovery solutions. In addition, this project aimed to provide an overview of the P status in agricultural soils of sensitive areas in the BSR and to determine the risk of P loss to water bodies from these areas. To this end, methodological research was performed, comparing and inter-calibrating different soil P tests applied in the Baltic Rim countries to assess plant available P as well as P loss potential. By establishing the *Baltic Forum for Innovative Manure Management Technologies,* transnational knowledge exchange and collaboration between researchers, industry stakeholders and policy makers was facilitated, promoting the integration of recovered nutrients into the agricultural economy.

The focus of **BONUS PROMISE (2014-2017)** was on the *recovery of P from organic waste streams.* With global concerns about finite phosphate rock reserves, there was an increasing need to reduce dependence on mined phosphate fertilisers. The project aimed to evaluate, *refine and improve P extraction technologies from both urban and agricultural waste sources*, such as digestate, sewage sludge and livestock manure, and to *ensure that the recycled products were safe for agricultural use.* The main focus was on potential contaminants in recycled fertilisers. As organic waste streams can contain residues of antibiotics, pathogens and heavy metals, extensive research was conducted to determine how different processing methods affect their removal or persistence. The project investigated how these risk factors vary between different waste sources and what measures could be taken to minimise the risk of contamination when recycled fertiliser is used in agriculture. An important outcome was that the digestion process has only little potential to reduce organic and inorganic contamination. With respect to pathogenic microorganisms, a stricter control of process parameters in biogas plants was identified as crucial. It was also shown that thermo-chemical treatment can significantly reduce both inorganic and organic contaminants, and destroy pathogenic microorganisms - however most of the organic matter content will also be lost. Based on these findings, regional nutrient recovery and best management strategies that considered site-specific conditions were proposed.

As efforts to improve nutrient recycling progressed, it became clear that one of the major challenges in manure management was the lack of standardised methods for assessing the nutrient content of manure. Without reliable and comparable data on manure composition, farmers struggled to optimise fertilisation strategies, leading to inefficiencies in nutrient use, potential over- or under-application of fertiliser and increased environmental risks from nutrient runoff. Likewise, policy makers and extension services faced difficulties in developing coherent nutrient management regulations, as inconsistencies in manure data between regions hindered the formulation of effective policies. **Manure Standards (2017-2019)** addressed these challenges by providing a *harmonised framework for manure sampling, nutrient analysis and data interpretation* across the BSR. The core objective was to *enable more efficient agricultural use of manure* by improving the accuracy of nutrient content estimation and integrating this knowledge into farm-level decision making and regulatory frameworks. A key achievement was the development of standardised protocols for the analysis of N and P in manure that allow for reliable and comparable nutrient assessments across all Baltic Rim Countries. In addition, *calculation tools* were developed to help farmers and extension services to better estimate the nutrient value of manure *based on standardised reference data.* By integrating standardised manure composition data into national and EU-wide nutrient management plans, policy makers were better equipped to develop consistent regulations that control nutrient application rates, helping to prevent over-fertilisation and water pollution while ensuring adequate nutrient supply to crops.

Manure Standards was a milestone in improving the efficiency of manure use. Still, there was an urgent need to translate its findings into practical policy frameworks and management strategies that could be implemented at the farm, regional, and national levels. The **SuMaNu platform (2019-2021)** was designed to bridge this gap by integrating scientific research into governance structures, ensuring that sustainable manure and nutrient management is effectively regulated and incentivised. Building on the results from several previous projects, including Baltic Slurry Acidification (investigating techniques to reduce ammonia emissions from manure), Manure Standards, GreenAgri (promoting environmentally sound organic manure management) and BONUS PROMISE, SuMaNu consolidated existing knowledge into *coherent recommendations for improved nutrient management across the BSR.* The project provided guidance on how to include manure-based fertilisers in agricultural nutrient management plans in line with existing EU and HELCOM regulations. *Technical guidelines on manure storage, processing and application* were developed to help farmers and policy makers adopt best practices to optimise N and P use efficiency and reduce nutrient loss. These guidelines emphasised the importance of *proper manure treatment technologies,* such as anaerobic digestion, composting and solid-liquid separation, which help preserve nutrient value while reducing greenhouse gas emissions and water pollution. SuMaNu actively promoted *regional nutrient redistribution strategies.* It was proposed to rebalance nutrient distribution by advancing the transport of surplus manure from livestock-intensive areas, processed into high quality, transportable recycled fertiliser, into growing regions suffering from nutrient deficiencies due to a lack of organic fertiliser. Thus, SuMaNu was instrumental in *establishing the policy and regulatory framework needed to implement sustainable manure management practices at transnational as well as national and regional level.*

LEX4BIO (2019-2024) was launched to explore how bio-based fertilisers (BBFs) could replace synthetic fertilisers in modern agriculture. The project aimed to *reduce Europe's dependence on mineral N and P fertilisers by optimising the use of recycled nutrients from organic sources.* One of the key achievements was the *mapping of regional nutrient surpluses and deficiencies* across Europe. Extensive data was collected on nutrient stocks, flows and imbalances, helping to identify opportunities for more *efficient nutrient redistribution.* The results indicated that, while synthesised N is still needed in the future for adequate crop supply, BBFs could most likely cover a large portion of the actual P demand, since many European agricultural soils can contribute large amounts of legacy P to satisfy plant needs. LEX4BIO also carried out *life cycle assessments* for different BBF production technologies, including composting, anaerobic digestion, struvite precipitation and thermochemical treatments, analysing their nutrient recovery efficiency, economic feasibility and environmental impact. A major focus was on *assessing the fertilising potential of a large number of marketed BBFs in growth trials under different climatic and soil conditions.* The results demonstrated that *BBFs can be as effective as synthetic alternatives in supplying N and P to arable crops.* Products containing organic carbon may also provide long-term benefits for soil quality. The analyses included *potential contamination* with organics and inorganics as well as pathogens. It could be demonstrated that the investigated BBFs kept all applicable EU benchmarks or threshold limits, indicating that these *products do not pose a risk to human, animal or plant health, to safety or the environment.* Based on the results, *socioeconomic and political recommendations* were provided for farmers, policy makers and industry stakeholders on how to optimise the use of BBFs, ensuring that recycled nutrients are used efficiently while minimising environmental risks.

LEX4BIO was instrumental in providing the scientific basis for the integration of BBFs into European agriculture and thereby helped to lay the foundations for the next phase: **CiNURGi (2023–2026)** puts these findings into practice by testing different recycled nutrient fertilisers (RNFs) in vegetation trials together with industrial partners. In these trials, *products already available on the market are investigated for their practical applicability in sustainable agriculture,* with a focus on soil health, nutrient efficiency and environmental impact. The results provide valuable insights into how well these products contribute to closing nutrient cycles and reducing reliance on conventional mineral fertilizers. At the same time, *CiNURGi actively supports the development and refinement of new, innovative RNFs by providing targeted financial support to help bring them to market.* By promoting technological advances and scaling up promising solutions, the project aims to ensure that these next-generation fertilisers are both economically viable and environmentally sustainable.

Through this dual approach - evaluating existing solutions while fostering innovation - **CiNURGi** thus continues to contribute to the long-term goals underlying the last two decades of agricultural research in the BSR: closing nutrient loops by recycling nutrient rich waste streams for fertilisation, reducing pollution and promoting a resilient, sustainable agricultural system in the BSR and beyond. Future efforts must focus on enhancing economically viable large-scale implementation of safe recycling technologies, increasing farmer adoption of recycled products, and strengthening regulatory and financial support to fully integrate circular nutrient solutions into sustainable agricultural systems.

Expert article • 3782

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SARI LUOSTARINEN

How to locate nutrient resources in the BSR?

Expert article • 3783

Nutrient recycling aims at reusing nutrients already utilized in human activities. This approach reduces the need to use mineral resources, such as phosphorus, or to bind atmospheric nitrogen, thereby minimizing related environmental impacts. These actions are expected to improve overall nutrient use efficiency.

Agriculture is a major nutrient user as the crops produced need especially nitrogen and phosphorus for their growth. The entire food system, including also food processing and consumption, utilizes and transports nutrients, with the majority eventually ending up in various side streams or being lost to the environment. To close the nutrient cycles, these side streams need to be recycled back to agriculture, and losses at each step of the system minimized. Additionally, side streams from other industries may contain nutrients that can be recovered.

The potential for nutrient recycling depends on where and how much of nutrient-rich side streams are produced. Mapping these side streams and their locations requires extensive data on production and consumption to quantify the different side streams and their nutrient content. This information is a prerequisite for planning measures to recover nutrients in a form usable for agricultural production.

The most significant nutrient-rich side stream is livestock manure. The nutrient content of manure can be calculated by multiplying the number of different animals produced in a country or region and coefficients of average nutrient content for each manure type per animal category. If the animal data includes farm information, the location of manure can be simultaneously identified.

Municipal source-sorted biowaste from households, restaurants, stores etc. is another significant waste fraction for nutrient recycling. EU member states around the Baltic Sea are required to monitor its production per capita and this data can be multiplied with population data to estimate the quantity and location of the biowaste. Using a coefficient of average nutrient content, the amount of nutrients to be recycled can be quantified.

Similarly, using per capita data on the production of sewage sludge per country, its quantity and location can be estimated. The nutrient content can be determined using information on its average nutrient coefficients.

Data on industrial nutrient-rich side streams vary among the countries surrounding the Baltic Sea, depending on the industrial production of each country. Significant nutrient contents are usually found in various side streams from the food processing industry. The location of origin can be identified per production plant.

When these different nutrient-rich side streams are aggregated, they provide an opportunity to compare their nutrient recycling potential to the fertilization need of a country or a region. In its simplest form, the total nutrients can be compared to the utilized agricultural area; e.g. kilograms of phosphorus per hectare. This comparison can be further amplified by considering also the crops grown and their fertilization requirements, along with the conditions and regulation of the region studied.

The higher the result per region, meaning the more recyclable nutrients available compared to the fertilization need, the more important it is to efficiently recycle the nutrients within that region. In cases of clear surplus, some nutrients need to be transported outside the region to areas in need. Such regions of surplus and deficit can be identified in all Baltic Sea countries, with surpluses typically found in areas of dense livestock production or high population density.

The comparison between the availability of recyclable nutrients and the need for fertilization forms the basis for planning and implementing practical measures to recycle nutrients. The available side streams and the need for transportation determine the types of technological processes and/or cooperative measures between actors that are required.

This data is also the basis for planning policy measures to enhance nutrient recycling. It indicates where and what types of incentives and regulation are needed. It also provides a means to monitor the progress of nutrient recycling within a country or region.

The more nationally collected and measured data available for mapping nutrient-rich side streams, the better the data describes the national situation, rather than providing a general indication. While general coefficients offer a good start for identifying, monitoring, and supporting nutrient recycling, statistics should be developed in all Baltic Sea countries to improve data collection for nutrient recycling purposes. Currently, there are many gaps that need to be filled.

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The changing European ashscape

Expert article • 3784

Europe is undergoing unprecedented changes in its energy production. There has been a steep decline in the use of fossil fuels and peat due to the green/sustainability transition goals and the Russia´s war in Ukraine with related sanctions. At the same time, waste-to-energy conversion (e.g., incineration of municipal solid waste and sewage sludge) is expected to further increase as landfilling becomes a more and more discouraged waste management option. In the Baltic context, Estonia has significant oil shale utilization but, even though it is defined as a strategic energy resource, most of it will be phased out by 2030. However, power plants are not producing only the energy but also various ash fractions as side streams. Coal fly ash has been traditionally an important supplementary cementitious material (i.e., material replacing Portland cement clinker) in concrete. In fact, the combined decreasing availability of coal fly ash and blast furnace slag from iron production (these two are the most used supplementary cementitious materials) in the future may even create a small crisis in the cement industry. This is because most of cements contain a significant amount of clinker substitution (e.g., CEM III class can have only 5% of clinker). It has been estimated that coal fly ash use in cement decreases from 3 million tonnes (or 2% of cement content) in 2020 to less than 1 million tonne (less than 1% of cement content) in 2050 according to the European Cement Association.

The European Union member states are generating 28 million tonnes of ashes from municipal solid waste, biomass, and sewage sludge incineration. Even though some of these ashes are utilized in certain low-value applications, such as municipal solid waste incineration bottom ash as in earthworks or sewage sludge ash as soil supplement in agriculture, a large fraction is still landfilled (for some ash fractions, more than half). These ashes are rich in silicon, calcium, and aluminum (the main elements required for cementitious materials), but they also contain significant amounts of recoverable base and precious metals, nutrients, and even rare earth elements. In fact, certain ashes nearly match or even exceed the currently exploited crude ores in the content of the valuable elements. For example, the phosphorus content of sewage sludge ash varies typically within 35–99 g/kg while the phosphorus content of ores can be 110–160 g/kg. Another example is zinc in municipal solid waste fly ash with a 9,000–70,000 mg/kg content in comparison zinc ores of 50,000–150,000 mg/kg.

To tackle these challenges, the European Commission has funded a project *Integration of Underutilized Ashes into Material Cycles by Industry-Urban Symbiosis* (AshCycle, www.ashcycle.eu) from the Horizon Europe programme. The project takes a holistic approach for the abovementioned ashes by addressing the resource recovery potential, required pretreatments, and their utilization for example as supplementary cementitious materials, raw material for completely cement-free binders (i.e., alkali-activated materials), sand and gravel replacement, CO2 absorbing materials, or adsorbent granules for water treatment. The project partners (total 27 from eight countries) represent universities and research institutions, powerplants, waste management and recycling companies, water treatment, construction material industry, and there is also a company developing an AI-based software supporting the ash utilization. The technical parts of the project focus on the recovery, pretreatment, and utilization approaches for ashes first in laboratory and then verifying them in pilots, which range from a few kilograms to tens of tons in their scale. Examples of the pilots include electrodialytic resource recovery, concrete products (e.g., paving blocks, street furniture, barrier elements), fired or unfired bricks, and ash granules for road subbase. The learnings from the pilots are used for sustainability assessment and developing models for the industry-urban symbiosis (i.e., evaluating the material flows and business possibilities between different actors).

Based on the already executed pilots, some observations can be made. One challenge is the lacking recognition of the addressed ashes by the existing concrete standards (this is also addressed in the project). Ash pretreatment (e.g., milling, washing, or chemical treatment to remove harmful elements or to improve ash properties) is a key operation enabling its further use. More industrial actors would be needed for this role, that is, between the ash producers and for example construction sector to ensure consistent and high-enough quality raw material. To make such businesses and the required investments more appealing, there should be more policy incentives, for example via banning the ash landfilling completely. However, the key overall message is that there are no insurmountable technical obstacles for utilizing the currently underutilized ashes.

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Urine's role in farm-to-fork-to-farm cycles

Expert article • 3785

Each of us produces, on average, 1.5 liters of urine every day. Remarkably, the nutrients in this urine are enough to fertilize 500 g of wheat grain—sufficient to bake a loaf of bread. But instead of treating urine as a valuable resource, we dispose of it as waste.

Why urine?

Nutrient runoff from farms is often blamed for polluting waterways, fueling algal blooms like those in the Baltic Sea. But agriculture isn't the only source of the problem—our own bathrooms play a significant role.

In Sweden, even with some of the world's most advanced wastewater treatment plants, a third of all nitrogen and phosphorus pollution in surface waters comes from human waste. With every flush, valuable nutrients are lost, turning a potential resource into a pollutant.

What's going on?

When we flush, urine, which is rich in nutrients, gets mixed with the rest of our household wastewater. While urine makes up only 1.5 liters of the 170 liters of wastewater each person produces daily, it carries the majority of the nitrogen and phosphorus. By the time urine reaches a municipal wastewater treatment plant, removing these nutrients from water becomes incredibly complex and inefficient, requiring large infrastructure, chemicals and energy. Which is partially why treatment plants are only required to remove about 70% of these nutrients, with the rest released into surface waters—fueling algal blooms.

What can we do?

At Sanitation 360, we have developed an innovative solution to capture all the nutrients in urine and transform them into a concentrated, solid fertilizer compatible with modern farming equipment.

For the past 5 years, we have been demonstrating the paradigm shift in how urine should be managed. Through partnerships with key stakeholders, we have collected over 25,000 L of urine, processed it into fertilizer, and supplied it to barley farmers who have confirmed that our bio-based fertiliser performs just as well as synthetic fertilisers. The harvested barley has then been brewed and beer quality tested by Gotlands Bryggeri as part of our P2GreeN project. This collaboration showcases a true farm-to-fork-to-farm cycle—where nutrients are returned to the soil instead of being lost as waste.

We are currently developing three urine treatment systems targeting different customer needs: 1) Indoor Household-scale system (15 L per day treatment) – Ideal for properties with on-site sanitation, offering a quick return on investment by reducing wastewater management costs and providing a local source of fertiliser; 2) Passive solar drying outdoor system (10 L per day treatment) – designed for seasonal use or regions with warmer and sunnier climates, making it a low-energy, sustainable solution; and 3) Large-scale system (200 L per day treatment) – Suitable for high-traffic locations such as football arenas, where large volumes of urine are collected in one place.

Stakeholders, including municipalities and private companies, see the potential of our technology to reduce environmental impact and and ease pressure on wastewater infrastructure. For example, we have an installation at the head office of VA Syd in Malmö as part of our REWAISE project. VA Syd is a water and wastewater utility that is keen to scale up our system. Across Europe, many wastewater treatment plants are either at or reaching capacity, limiting their ability to handle wastewater from new urban developments. Our solution offers a decentralized alternative, helping to extend the lifespan of existing wastewater treatment plants. Similarly, the City of Stockholm is interested in our technology as it spends over 1 million SEK annually on imported fertilizer for its green spaces, while at the same time, urine, a rich source of nutrients is being flushed away.

With the new CiNURGi project, we are now in the planning phase for our first permanent large-scale installation, a 3 million SEK project that represents a major step towards mainstream adoption of urine recycling.

By rethinking how we handle urine, we can transform waste into a resource, closing nutrient loops and building a more sustainable future.

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Pyrolysis of side streams rich in nutrients

Expert article • 3786

Current geopolitical situation and environmental concerns are strong drivers to enhance nutrient recycling. Phosphorus (P) and phosphate rock are on EU´s critical raw material list and nitrogen (N) fertilizer production relies largely on imported natural gas. Europe is divided into areas with excess P in intensive animal production areas, and those where P fertilizers is needed. This recalls continental scale rebalancing of nutrient streams. Thus, one driver for intensive biomass processing is the possibility to concentrate nutrients and/or make recycled fertilizer easy to store and transport longer distances. Industrial and municipal organic waste streams are available broadly, but concerns related to organic contaminants, such as pharmaceuticals, hormones and industrial chemicals, are increasing. Solution is sought from the Intensive processing technologies capable of reducing such risks.

Pyrolysis is a thermochemical process where biomass is heated above 350 °C in the absence of oxygen. It produces dry biochar that is easy to transport and store. Traditionally the technology is used to produce biochar from wood-based biomasses, but also sewage sludge, manure and nutrient-rich feedstocks from industrial sources can be used as raw materials.

In pyrolysis process organic matter transforms to more recalcitrant form, which contributes to soil long term carbon reserve in decadal or centennial time scale. Pyrolysis significantly reduces the content of many organic pollutants while P and potassium (K) are concentrated to the char fraction.

The other side of coin is that the processing requires energy intensive drying of the feedstock and investments in the technology. In addition, N is partly lost in the process, and plant availability of P and remaining N decreases. Also, non-volatile heavy metals present in the feed stock concentrate to the biochar, and relatively inert char does not offer food for soil microbes as original fresh organic matter does. Regardless of vast scientific literature, practical agronomic experience on the use of biochars produced from nutrient-rich biomasses is still rare.

It is no wonder that there is no consensus whether pyrolysis technology can facilitate nutrient recycling. And if it does, in what circumstances? Currently, there are existing industrial scale facilities for sewage sludge pyrolysis. One driver to this development has been a concern related to harmful substances, which hinders the agricultural use of sewage sludge. Sludge pyrolysis can be seen as an alternative method to sludge incineration with better possibilities for carbon and nutrient recycling.

In addition to pyrolysis, other thermochemical conversion technologies should also be considered in valorization of organic side streams. Hydrothermal carbonization (HTC) is a process suitable for liquid and slurry-like materials without drying. HTC is operated in moderate temperature (180–250°C) and pressure (15-25 bar). The degree of carbonization is lower than in pyrolysis, making the HTC char fraction less stable in soils than inert pyrolyzed biochar. More reactive HTC-chars may provide better food for soil microbes and have a positive impact on soil processes. HTC technologies could be potential for biomasses requiring "intensive hygienization" to remove for example health or plant pathogens. Suitability of HTC process for food industry side-streams, and the agronomic potential of the char-fraction, is currently being studied in Finland as a part of Horizon EU funded project DeliSoil (https://delisoil.eu/).

In the case of livestock manure, intensive processing is motivated largely by the need to reduce logistic costs. Solid-liquid separation facilitates the spreading of P rich solid fraction to the fields where P is needed. However, if longer distance transport is required, further processing with, for example, drying, pelletizing or even thermochemical conversion might be needed. Due to the current economic constraints, the increase in manure processing is not foreseen without stronger policy steering and appropriate incentives to take actions in practice. A Horizon EU funded project GREENHOOD is one timely project targeting to balance regional nutrient balance and co-develop governance solutions to support utilization of biobased fertilizers (https://greenhoodproject.eu/). In addition, an Interreg Baltic Sea Region funded CiNURGi -project will develop nutrient recycling and recovery strategies and policy coherency within the Baltic Sea region (https://interreg-baltic.eu/project/cinurgi/).

In conclusion, while the scientific literature on thermochemical processing of nutrient-rich biomass is vast, practical knowledge of generated recycled fertilisers remains limited, particularly in terms of long-term soil experiments. Variability in raw materials and processing conditions can significantly impact the properties of the resulting (bio) char product, highlighting the need for more precise categorization of both char products and raw materials. Further research is essential to establish a robust foundation for legislation and guidelines.

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The Baltic Sea region's bio-waste potential

Expert article • 3787

A powerful but underappreciated climate fix is in our kitchen bins. Across the Baltic Sea region, most food scraps like potato peels and coffee grounds are still dumped or burned, releasing methane emissions or CO2 while wasting valuable resources. Globally, landfills generate about 10% of human-caused methane emissions—a major climate hit for something as mundane as rotting food.

When properly treated, bio-waste transforms into high-quality compost or digestate that nourishes soils, fertilises crops, and contributes to carbon sequestration. Yet in the EU, only 26% of available kitchen waste is collected separately and composted. Of the 60 million tonnes of kitchen waste produced annually in Europe, only 15 million tonnes are properly recycled.

Every discarded food scrap represents a missed opportunity to reduce emissions and replenish soils. Currently, 60-70% of European soils are classified as unhealthy, and nearly half suffer from low organic matter content—a concerning reality given that food security depends on soil quality.

With optimised collection, we could capture up to 35 million additional tonnes of bio-waste. Achieving the EU's 65% recycling target by 2035 would double the area benefiting from compost application, contributing to healthier soils and more sustainable agriculture. High-quality compost and digestate reduce dependence on chemical fertilisers, most of which are imported from Russia.

This is particularly relevant for the Baltic Sea—one of the world's most polluted seas—where agricultural nutrient runoff drives eutrophication. Increasing compost and digestate production could help mitigate this pollution while improving soil health.

Separating kitchen waste also improves recycling efficiency. Yet many EU member states struggle with separate collection, and parts of the Baltics lack the infrastructure to process bio-waste. Not coincidentally, these countries also rank among Europe's top waste burners, creating a harmful dependency on incineration.

This gap can only be bridged through improved bio-waste management. Encouragingly, evidence shows that well-designed systems can quickly boost both the quantity and quality of collected bio-waste. Sharing best practices, such as Milan's 87.5% separate collection rate, can help lagging cities catch up.

Progress is emerging across the Baltic region. By 2022, Denmark required all municipalities to implement separate collection. Estonia made door-to-door collection or home composting mandatory by 2023. Finland extended door-to-door bio-waste collection to all housing properties in centres with more than 10,000 inhabitants.

However, the EU's separate collection mandate alone is insufficient. Without proper guidance, binding targets, and effective monitoring, underperforming systems will persist. Some countries lack treatment capacity, such as anaerobic digestion plants or composting facilities, to process increased organic flows. Research conducted within the LIFE BIOBEST project reveals several strategies to close regulatory gaps and transform bio-waste management across all governance levels:

1. Implementing higher landfill and incineration gate fees coupled with strategic disposal taxes to level the playing field for proper bio-waste management and encourage investments in efficient collection and treatment methods.
2. Establishing binding targets for the quantity and quality of bio-waste captured, alongside robust data monitoring, to accelerate adoption of effective practices.
3. Prioritising communication and citizen engagement—even the best-designed system fails if residents don't understand why and how to participate. Municipalities that invest in communication while providing user-friendly tools like kitchen caddies and compostable bags have demonstrated notable increases in collection rates.

This decade is decisive for climate action. Diverting organics from landfills and incinerators offers a quick, cost-effective way to reduce GhG emissions. The Baltic Sea would benefit from reduced nutrient leaching into waterways, mitigating pollution. The region has an opportunity to demonstrate a truly circular future where organic resources return to enrich both the economy and soil, completing nature's intended cycle.

Transforming waste systems requires coordination and upfront investment, but the goal is achievable. With EU regulations in effect, every day of delay means more methane emissions and wasted resources. Policymakers, businesses, and citizens must collaborate to enforce mandates, invest in composting infrastructure, develop biogas capacity, and embrace zero-waste practices. The Baltic region can transform today's leftovers into tomorrow's fertiliser, fuel, and climate solutions - proving that what we call "bio-waste" is actually a valuable resource awaiting its proper use.

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Poultry manure – nutrient recycling and beyond

Expert article • 3788

In Poland, production of poultry (including laying hens) has been on the increase for many years. According to the Statistics Poland (2024) the poultry production was reported at 130 959 in 2010, 182 473 in 2020, and 195 144,5 in 2023 (in thousand heads), making around 20% of EU market share (Statistics Poland, 2022). Now, there are over 1 300 poultry farms operating in Poland and the number is dynamically rising. Such an intensive industrial production of poultry (for eggs and meat) with a predominating cage breeding system demonstrates considerable environmental footprint and sustainability challenges. This is mostly due to poultry manure which is generated in large quantities in poultry farms. For example, it is estimated that chicken broilers produce about 65 kg whereas laying hans about 150 kg of manure per day per 1 000 birds (after Dróżdż et al., 2020). Managing these large quantities of poultry manure requires a comprehensive approach to assure overall safety and nutrient recycling.

Poultry manure as a source of nutrients

The composition of poultry manure depends on a number of factors, including a breeding type and a breeding system, seasonality, but generally poultry manure is high in water (68-73%) and contains nitrogen (3-5%), phosphorous (0.9-3.5%) and potassium (1.5-3%) (after Kacprzak et al., 2022) making it a valuable natural fertilizer or a feedstock for production of various bio-based fertilizing products and soil improvers. Typical and quite common practices for managing poultry manure in Poland include direct soil application through land spreading of unprocessed poultry manure as well as applying different fertilizing products such as poultry manure derived composts, dried poultry manure in a form pellets, granules, etc.

Facing challenges and limitations

Although poultry manure is rich in nutrients such as nitrogen, phosphorous and potassium – making it a valuable natural fertilizer - it also contains various microcontaminants such as pharmaceuticals, heavy metals and also microorganisms which are potential threats to the environment, specifically to agricultural soils. Handling, transporting and managing of poultry manure – especially from small and medium sized farms located in non-rural areas – poses many difficulties. Mostly, this is linked to high contents of moisture and organic matter, thus high susceptibility to decomposition contributing to e.g. gaseous emissions of ammonia, nitrous oxide, methane. Land spreading is no longer a sufficient method for management of unprocessed poultry manure to assure nutrient recycling and environmental safety. Composting of poultry manure still faces technological challenges due to high content of nitrogen, and thus, potential loss of nutrients through gaseous emissions (mostly ammonia) and leaching. Therefore, the excessive quantities of poultry manure need to be properly handled and managed to avoid air, water and soil contamination.

From poultry manure to a versatile material with interesting properties

Poultry manure can be also managed with the use of pyrolysis to obtain biochar. Pyrolysis is a well-known thermal conversion of various types of biomass into biochar – a solid, carbon rich material with interesting chemical and physical properties such as chemical composition, specific surface area, porosity and presence of various surface functional groups. With pyrolysis parameters (e.g. pyrolysis temperature and heating time) and also different chemical and physical modifications biochars from poultry manure can be tailored to address specific applications.

Poultry manure derived biochars – depending on their properties – demonstrate high potentials to be used in various in-soil applications but also in many other areas. Primarily, biochars from poultry manure are used as soil improvers or components in developing bio-based fertilizing products to reduce the use of non-renewable fossil based mineral fertilizers. What is more, these biochars can be used as partial or complete peat substitutes in horticultural growing media. They can also function as sorbents to remove various contaminants from water and wastewater or prevent excessive gaseous emissions e.g. ammonia emissions during composting. For over two decades now, the properties and novel applications of different types of biochars have been excessively studied and new applications have been explored. One of these new applications is the use of biochar for developing bio-based and biodegradable plastics.

Biochars are considered potential renewable and sustainable fillers for developing bio-based and biodegradable plastics for agricultural use (so called "agribioplastics"). Bio-based and biodegradable plastics are alternatives to the conventional fossil-derived plastics which usually do not biodegrade, and thus are considered a serious source of microplastic pollution in agricultural soils. The idea is to incorporate biochar into the composite or blend and reduce the use of biodegradable polymers/ blends in single-use "agribioplastics" such as those used in growing ornamental and edible plants (e.g. clips, supports, ties or mulching films). After harvesting these biochar-filled "agribioplastic" accessories mixed with plant residues can be managed through industrial composting. This assures efficient end-of-life management of plant residues and prevents from microplastic contamination.

Future outlook

With all the research work and field testing performed so far (e.g. Nutri2Cycle, H2020, 2018-2023), there is no doubt that poultry manure is a valuable source of nutrients and a feedstock for various products such as bio-based fertilizers or soil enhancers. With the current dynamics in poultry production in Poland it is anticipated that the quantities of poultry manure will be on the increase. Therefore, new solutions for sustainable and circular nutrient management will be needed to work towards the goals set by the European Commission in the Farm to Fork Strategy, primarily to decrease nutrient losses by at least 50% and to reduce fertilizer use by at least 20% by 2030. Poultry manure derived biochar – a versatile material with interesting properties and applications – is considered a promising sustainable and circular solution to address the most pressing environmental issues and contribute to decrease in nutrient losses, mitigation of gaseous emissions and reduction of non renewable resources (being an alternative to peat or a filler in "agribioplastics"). Although, in Poland scaling production of biochars from different types of feedstock still remains a challenge, there is a lot of research work currently being done to overcome technological issues. In addition to that, currently launched initiatives such as these within the AGRI-BIOCIRCULAR-HUB project (HORIZON-WIDERA-ACCESS: Excellence Hubs, 2025-2028) with various organizations from Ukraine, Latvia, Poland, Belgium and Spain are to enhance development and adoption of smart and circular technologies and innovations towards sustainable agriculture.

Expert article • 3788

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Moving from damage control to circular approaches

Expert article • 3789

The European countries have been able to significantly reduce nutrient emissions to surface waters over the last decades. This has certainly also been true for the countries around the Baltic see. Nevertheless, we still have remaining challenges to further reduce these loads even though significant steps have been taken. On the other hand, our society is also increasingly realizing that access to nutrients is also of enormous strategic importance because without these nutrients are crucial to produce our food and feed the European population. Therefore, we need to realize better that controlling nutrients in our environment is not only about the quality of our surface water but also how we manage our food production in a more sustainable and circular way. Although current approach to control of nutrient discharges to surface water and the sea has been mostly effective from a water quality point of view it is not sustainable nor circular.

Issues in the current control of nutrients

Nitrogen and phosphorus are the most important nutrients that need to be controlled and both nutrients require different approaches. Our sewage treatment plants destroy more than 80% of the bound nitrogen in the sewage by a biological process called nitrification and denitrification using a lot of energy and part of the dissolved carbon in the sewage which is then not available for other uses. Also, in the last years we have learned that this process can produce significant amount of the potent greenhouse gas nitrous oxide (N2O) if not controlled properly. On the other hand roughly 1% of the world's energy use is related to the conversion of nitrogen gas from the atmosphere into bound nitrogen for use in our fertilizers and a similar amount of energy is used for the removal and destruction of bound nitrogen in sewage treatment plants.

Phosphorus is now mainly removed by concentrating the phosphorus in the sewage sludge produced in sewage treatment plants, either by stimulating biological uptake (enhanced biological phosphorus removal or EBPR) or by dosing coagulants like iron salts which bind with the phosphorus. Thus, phosphorus removal increased the production of waste and requires a sensible destination of the sewage sludge loaded with the phosphorus. In countries where the sludge is incinerated or landfilled the phosphorus is lost for future generations. In other countries the sludge is used in agriculture but not always is the application rate truly in balance with the phosphorus need of the crops. Too high applications of sludge would then again lead to eutrophication issues. On the other hand phosphorus is considered a critical raw material by the European Union since it is strategic for our food production because EU countries do not have significant sources of phosphate rock in Europe. In the current situation the cost for removal of phosphate from sewage sludge is nearly as high as the production of phosphorus fertilizer from phosphate rock.

Upgrade or redesign?

As of January 1 of 2025 the revision of the Urban Waste Water Treatment Directive has entered into force and this revision will require EU member states not only to comply to stricter effluent limits but it also intends to stimulate circular use of nutrients. Therefore now is the time to plan for a new generation of sewage treatment plants and water utilities will have to decide if it is sufficient to upgrade existing plants or should we consider radical new concepts.

At Wetsus we focus on the development of new water technology in close collaboration with more than 50 academic chairs and 100 European industrial stakeholders. In this role we are at the forefront on developing new concepts to address the described challenges. What we see is that there are indeed options to become more circular. Some of these options can be used to retrofit existing sewage treatment plants while others focus on more radical changes. In the end we will need a healthy mixture of both retrofit and far fetching solutions to grow to more sustainable use of nutrients.

Examples of innovative concepts

Iron salts are commonly added to sewage treatment plants to bind phosphorus which then ends up in the sewage sludge as an iron-phosphorus mineral. It is expected that increasingly higher dosages of iron salts will be needed in the near future to comply to future effluent limits. Research at Wetsus has shown that a blueish mineral called vivianite is formed in the sludge and that it can bind up to 80% of all phosphorus in the sludge. This mineral is paramagnetic and that makes it possible to extract it from the sludges using magnetic equipment that is also used in conventional mining. In this way up to 60% of all phosphorus in sewage can be recovered while also recovering most of the iron. The recovered vivianite can be splitted to produce a phosphorus fertilizer while also recovering the iron for reuse. Also, there are interesting perspectives to use the material for production of lithiumironphosphate (LFP) batteries, a part of our current research. Our Finish partner Kemira is now commercializing this approach under the name of ViviMag®.

Another approach would be to adsorb the phosphorus on ironoxide adsorbents that can be regenerated after they are fully loaded with phosphorus. In this way the adsorbent can be reused continuously preventing the continuous dosage of iron salts. Our research has shown that via this approach one can achieve ultra low phosphorus concentrations (less than 50 ppb P) while also recovering the phosphorus. Our Dutch partners Aquacare and Royal HaskoningDHV have demonstrated this concept at pilot scale and are now working towards a first full scale application. This concept may also be used in a different way to remediate eutrophicated lakes by binding and recovery of the phosphate in a lake, either via a pump and treat approach or a more passive "tea bag" approach. New research is now underway to combine this with nitrogen adsorbents and thus providing for a more sustainable way to remove nitrogen from sewage water.

Finally an even more radical approach would be to rethink our sanitation system. Reuse of sewage sludge in agriculture is hindered by concerns of a whole range of pollutants in the sludge. By staying closer to the source and separation of urine, black water and grey water one can prevent that human manure gets polluted by other pollutants and this could produce a new and more sustainable way to bring nutrients back to agriculture. Important real life examples of this concept have been introduced in Helsingborg (Sweden), Hamburg (Germany) and Sneek (The Netherlands).

Create room for experimentation
These are just examples from our own research but more solutions are possible of course. Our society faces challenges not only to maintain the the quality of our rivers, lakes and seas but will also need to addressing security of our food production and other resources. The examples show that we can do both at the same time. However, it does require room for experimentation to mature these new concepts, learn lessons and improve them. We see many of these concepts now reaching puberty and now water authorities, regulators and financers should create space for these adolescent technologies to explore the real world and become adult technology.

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Reductive P recovery from activated sludge in WWTPs

Expert article • 3790

Sewage sludge in the Baltic Sea catchment

Overall, around 52 million people were connected to tertiary wastewater treatment plants (WWTPs) in the Baltic Sea catchment area in 2020, representing 72% of the total population. These WWTPs largely reduce (70% – 90%) the discharge of nitrogen and phosphorous into the Baltic Sea. While nitrogen is transformed to gaseous N2 to a certain extent during wastewater treatment, all of the phosphorous (P) is "stored" is the sewage sludge. This makes sewage sludge an interesting source as fertilizer in agriculture.

The Baltic Sea countries follow different approaches to use the sludge. The majority of the countries field apply most of their produced sludges in agriculture directly or after composting (e.g. Denmark, Estonia, Lithuania, Sweden). However, in Germany, that produces 60% of the Baltic Sea related Phosphorous load in sewage sludge, most of the sludge is incinerated. There, field application of sewage sludge was more and more reduced because of environmental concerns.

Due to the EU Urban Wastewater Treatment Directive, P recycling from sewage sludge or wastewater will become more important in all EU countries. To recycle at least half of the P from wastewater (or sewage sludge) could be an envisaged aim for all European countries under the umbrella of the EU directive. Similar aims are found in current legislations in Austria, Switzerland and Germany already.

Germany is a current hot spot of P recycling activities

In Germany, starting from the year 2029, wastewater treatment plants are required to recycle phosphorus if the phosphorus content exceeds 2% in the dried sewage sludge. Bigger plants need to recycle P from 2029 on, smaller ones from 2032. It is expected that most of the phosphorous will be recycled in form of fertilizers or prerequisites for fertilizers.

Because of the legal changes in Germany, the country has become a focal point for phosphorous recycling technologies. Technologies are competing but so far none of the technology providers has proven that their technology can operate steadily. Experts assume that most of the sewage sludge will be treated at centralized sites. In this case, mono-incineration of sewage sludge is the first technological step to enable phosphorus recovery. It is followed by physico-chemical processes that extract phosphate from the ash and concentrate it. The end products can be for example phosphoric acid or tricalcium phosphate. However, many established pathways for sewage sludge recovery, such as co-incineration in the cement industry, are lost due to mono-incineration of the sludge. In addition, in less populated areas, long and climate unfriendly transports are required to bring the sludge to the centralized phosphorous recycling facilities.

A closer look to phosphorous recycling at WWTPs

On site, P recycling technologies have not managed to recycle more than 50% of the P input into the WWTP, so far. Why is this so? It is necessary to have a closer and more technical look into the WWTP: Basically, there are two ways to reduce the P from wastewater. The biological uptake of P into the microorganisms at a WWTP requires a special treatment regime inside the plant. The process has its specific challenges and not all plants are able to remove enough P from the wastewater constantly. The second option is the precipitation of P with iron or aluminum salts. It requires the dosing of Fe and Al and it is the predominant technology used in WWTP. Even most of the WWTP that are using the biological P removal technology, dose Fe or Al certain extent to reliably reduce P in the effluent water.

Until now, only biological bound P in the sludge could be remobilized into the water phase and then precipitated in form of e.g. struvite. The key for higher P remobilization from wastewater (or sewage sludge) is to break up iron-phosphate salts again, after these salts were deliberately formed. Besides excessive use of acid or alkaline, reductive processes are able to remobilize P from FeP salts. Such a reductive method for P recovery was developed as an on site technology in Germany.

Process description

In a nutshell, the whole recycling process covers five treatment steps. The activated excess sludge in a WWTP is first reduced by sulfur-containing reducing agents. It is the time limiting step of the process. An average residence time of 10-24 hours is optimal. The next three steps are fast and comprise slight acidification to a pH of 4, a heavy metal removal and a flocculation of the sludge for subsequent sludge dewatering. After sludge dewatering the remobilized phosphate is in the water phase. Now, it can be precipitated in the form of magnesium ammonium phosphate (struvite).

It is a well-known but not widely produced slow release fertilizer. It is listed in the EU Fertilizer Products Regulation as material that falls under the Component Material Category No. 12.

The remobilization grade depends on factors such as reduction time, wastewater temperature and dosage amount of the reducing agent. The P recovery process was tested continuously with the sludge of 5,000 person equivalents on a WWTP in Germany for three months. P recovery was maximum 70%.

This technology may overcome the current limitations of effective P recycling on WWTPs and may be the base for decentralized P recycling. However, as all other technologies, it must still prove its full scale continuous operation.

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Nitrogen recovery – one solution fits it all?

Expert article • 3791

The Baltic Sea is a unique water body and has been an area of economic interest for centuries. And while countries developed and their general wealth increased, the environmental condition of the Baltic Sea worsened in an alarming way. And although in the last decade some measures were installed to prevent a further worsening some key environmental issues remain, such as eutrophication caused by high levels of nitrogen and phosphorus from agriculture, wastewater, and industry. Despite efforts to reduce nutrient input, the recovery process is slow due to legacy nutrients already present in the ecosystem. Algal blooms have increased, leading to *dead zones* (hypoxia) where oxygen is too low for marine life to survive.

Between the reference period of 1997-2003 and the year 2020, the total input of nitrogen decreased by 12%. Despite these reductions, eutrophication remains a significant issue. The Baltic Sea continues to experience severe oxygen depletion, with over 80,000 km^2 of its bottom areas affected by hypoxia or anoxia as of 2019.

Efforts to reduce nitrogen effluent in the Baltic Sea include improving agricultural practices, better wastewater treatment, and implementing regulations to reduce nitrogen emissions. There are several strategies in place aimed at reducing nitrogen pollution and recovering ecosystems affected by nitrogen in the Baltic Sea. For instance, there's the Baltic Sea Action Plan (BSAP): It includes specific goals to reduce nutrient inputs (including nitrogen) from agriculture, wastewater, and atmospheric deposition. The BSAP emphasizes reducing nitrogen inputs by 20% by 2027 compared to 2007 levels and achieving a healthier marine ecosystem.

Additional to Improved Agricultural Practices, such as regional Nutrient Management Plans and Sustainable Farming Incentives a lot has been done towards Wastewater Treatment Improvements. Many countries bordering the Baltic have upgraded their wastewater treatment infrastructure to better remove nitrogen and other nutrients before they are discharged into the sea.

Nitrogen removal can be done by biological, chemical, and physical methods, with biological processes being the most used, namely nitrification and denitrification. However, they have certain drawbacks such as a high energy demand and a reduced efficiency in colder temperatures. Furthermore, state of the art nitrogen removal has two major issues: Nitrogen removal is the largest source of greenhouse gas emissions from a wastewater treatment plant, with up to 6% of the total nitrogen released as N2O. Also, in most of the processes, the nitrogen is only removed but not recovered. Since the production of nitrogen-based fertilisers is responsible for about 1% of all human-made carbon dioxide emissions via the Haber-Bosch process, one should start acting more circular by recovering nitrogen, when possible.

The Urban Wastewater Treatment Directive (UWWTD) introduces new requirements for wastewater treatment plants. Since plants in the EU with a size above 150.000 person equivalents must remove more nitrogen from the wastewater by 2039, as well as become energy neutral, e.g. via increased biogas production leading to a higher nitrogen load, it is clear that new innovative wastewater treatment solutions are needed.

The actual production of nitrogen based-fertilisers, the loss of nitrogen in wastewater treatment plants and the new regulation is a driving force for the implementation of innovative processes that both remove and recover nitrogen. One example for this can be the Aqua2N process.

Technologies to recover nitrogen loads can be beneficial in both reducing the load of water streams but also help reducing airborne emissions. EasyMining's Aqua2N acts on liquid waste streams with high concentrations of ammonium nitrogen, such as sludge liquor. Although this comprises only 0.5 - 1.5 % of a plant's total liquid flow, it contains 15 - 30 % of the total nitrogen load. By removing 95 % of the ammonium nitrogen in that stream, Aqua2N reduces both the nitrogen load and the carbon footprint of traditional plants. Furthermore, no nitrous oxide, a greenhouse gas 300fold more harmful than carbon dioxide, is emitted in the process. With the upcoming EU UWWTD the technology can help operators live up to the coming need to reduce nitrogen emissions.

While efforts to restore the Baltic Sea continue, recovery is slow, and climate change adds new uncertainties. Further reductions in nutrient pollution among others will be crucial. And although our very own Aqua2N technology can play its part in that development, technologies alone will not solve the problem: International cooperation among Baltic Sea nations is essential to tackle cross-border environmental issues effectively. Strong communication even with neighbouring countries that are not upkeeping the set agreements is crucial to ensure the future of the Baltic Sea and its vital role, it played for so long and for so many countries.

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The potential of source-separating wastewater systems

Expert article • 3792

Similar to the separation of waste in households, wastewater can also be separated at the source, separating the nutrient-rich but small flow of blackwater (wastewater from the toilet) from the voluminous greywater (all other wastewater streams from the household, e.g. from sinks, showers and kitchen appliances). The separate collection and management of blackwater and greywater has major benefits for society particularly regarding the protection of receiving water bodies, the recycling of plant nutrients from wastewater to food production as well as an efficient recovery of energy from wastewater streams.

In such a system, blackwater and greywater are transported in separate pipe systems, requiring an additional pipe ("two pipes out"). Using vacuum toilets and vacuum pipe systems for the collection of blackwater is highly beneficial as they require only a small flush volume (<1L), keeping dilution to a minimum. The highly concentrated stream of blackwater can thus be efficiently transported to a treatment plant for the production of biogas and fertilisers. The greywater is transported in conventional pipe systems and treated to be reused or discharged.

Our current wastewater system

Our existing wastewater infrastructure and management systems are built for linear, and not circular, management, hampering the possibilities of reusing resources connected to our wastewater (nutrients, water, energy, heat, organic matter) in a safe and efficient way, due to dilution and mixing of wastewater flows of vastly different characters. In many cases, stormwater and wastewater are transported in the same pipe; the transport and treatment of the diluted wastewater consumes energy and leads to sewer overflows during storm events. This discharge of untreated wastewater to the environment potentially leads to decreased biosecurity, especially where the natural waters are used as drinking water sources. Today's wastewater treatment plants are inefficient in recovering heat and energy from the wastewater as most of the heat is lost during transport and most of the organic material needed for biogas production is removed in the treatment processes. The aerobic processes at our wastewater treatment plants need aeration, which is energy demanding and emits laughing gas, a potent greenhouse gas. The recovery of plant nutrients is difficult and is today insufficient. Phosphorus can potentially be recycled to agriculture with sewage sludge but the sludge contains contaminants. Nitrogen can hardly be recovered despite the large demand of nitrogen fertiliser in agriculture. This demand is now met by fertilisers produced using the industrial Haber-Bosch process, which stands for 1% of the global CO2 emissions. The emissions to water caused by today's wastewater management systems are considerable, not only through overflows but also through the discharge of treated wastewater which contributes a considerable amount of nutrients, organic micropollutants and pathogens to the environment.

Existing implementations of source-separating systems

Blackwater systems have successfully been implemented in several city districts in Europe. Examples include the H+ development in Helsingborg (Sweden), Nieuwe Dokken in Gent (Belgium) and Jenfelder Au in Hamburg (Germany).

Main benefits of blackwater separation in summary

The main benefits of the separate management of blackwater and greywater can be summarised as follows:

1. Enabling the recirculation of plant nutrients
   As ca 90% of the nitrogen and phosphorus and ca 85% of the potassium of domestic wastewater is contained in the blackwater, it is an excellent stream to focus on for recovery and recirculation of these resources. While phosphorus recovery is theoretically possible from today's wastewater treatment plants, the share of nitrogen and potassium that can be recovered is low. In source-separated blackwater the recovery rates of nutrients are considerably higher, potentially increasing e.g. the recovery of nitrogen by more than 400%.
2. Receiving water bodies
   As blackwater systems transport the toilet waste in vacuum sewers, the risk for overflows of untreated wastewater is small, decreasing the risk of contamination of potable water sources and the environment with nutrients, pathogens and emerging pollutants.
3. Energy recovery
   As the collected blackwater is highly concentrated it can be directly treated with anaerobic digestion, producing up to 70% more biogas than in today's wastewater treatment plants. Most of the energy in wastewater, however, is heat which is mostly found in greywater (hot wastewater from e.g. showers, dish washers and washing machines) and can be more effectively reused when not mixed with the colder wastewater from the toilets.
4. Water savings
   Vacuum toilets used in blackwater systems use up to ten times less flush water than a conventional toilet, saving on drinking water resources.
5. More efficient treatment processes
   Most pharmaceutical residues in wastewater end up in the blackwater. With upcoming demands on pharmaceutical removal in the EU, collecting the blackwater separately allows for targeted pharmaceutical removal in a less diluted flow compared with a conventional wastewater.

Blackwater systems thus have the potential to increase nutrient recirculation and food security as well as saving on energy and water and protect receiving water bodies. A cost-benefit analysis of a new city district in Stockholm has shown that source-separating wastewater systems have a higher benefits:cost ratio than the state-of-the-art conventional wastewater system, in spite of the economies of scale working in favour of the conventional system. Because of all the advantages of source-separating wastewater systems it would be desirable that the consideration of these systems is mainstreamed into urban planning and development. That way we can get more systems implemented and build a new more sustainable infrastructure paradigm within the wastewater sector.

Expert article • 3792

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Sludge valorization in Baltic Sea Region

Expert article • 3793

Municipal wastewater treatment produces large amounts of sludge as a byproduct that presents both challenges and opportunities in a wider picture. In the Baltic Sea region around 4 million tonnes of municipal sludge, calculated as dry solids, is generated annually. One of the main environmental concerns in the Baltic Sea is the prevention of eutrophication caused by excess nutrients leading to algal blooms, oxygen depletion, and harm to the ecosystem. Municipal sludge is rich in phosphorus and nitrogen, and if not properly treated, these nutrients are likely to be released into water bodies. The sludge also contains contaminants like heavy metals and pharmaceuticals, which are difficult to remove with standard treatment methods. Therefore, effective sludge management is crucial to protect the environment and enhance sustainability.

Approximately 97% of the phosphorus and 9% of the nitrogen in municipal wastewater end up in the sludge during the treatment. Despite these high concentrations, around 50% of the phosphorus and nearly all the nitrogen in Europe remain unused because of regulations and limitations in recovery technologies. This unutilized portion could cover about 10% of Europe's phosphorus needs and 2% of its nitrogen fertilizer requirements. Currently, the EU is almost entirely dependent on phosphorous imports while 30% of needed nitrogen fertilizers are imported. The vulnerability of this supply chain was highlighted in 2022 when fertilizer prices arose due to the Russian attack on Ukraine and disruptions in the energy market. Municipal sludge is a reliable and locally available resource offering a potential solution.

In addition to nutrients, sludge contains a substantial amount of organic carbon, which could be utilized for energy and materials. Around 65% of the carbon in municipal wastewater ends up in the sludge, which contains about 40% carbon in its dry solids. However, the use of carbon from sludges remains underdeveloped. Biogas production through anaerobic digestion is the most common method, but it exploits only a small portion of the carbon's potential. Advanced technologies may allow the production of high-value carbon-based products, such as biochar for soil enrichment, activated carbon for water filtration, or even hard carbon for lithium-ion batteries.

Municipal sludge also contains inorganic compounds like iron and aluminum salts, which are used as coagulants and precipitation agents in wastewater treatment to remove solids and pollutants, as well as in the production of clean drinking water. In the Baltic Sea region, where protecting water quality is crucial, these chemicals are highly important. However, the mining and production of iron and aluminum salts are resource-intensive and have environmental impacts. Recovering these metals from sludge and reusing them in treatment processes follows the principles of a circular economy, reducing the need for raw materials and minimizing waste.

Despite these opportunities, a significant challenge remains in utilizing municipal sludge. Even when products derived from sludge are treated and deemed safe, they often face suspicions from consumers, farmers, and policymakers due to concerns of contaminants and long-term environmental impacts. This is particularly true in the Baltic Sea region, where environmental awareness is high. Overcoming this challenge will require more than just technological solutions. Transparent communication, rigorous safety standards, and thorough pilot actions to demonstrate the benefits of sludge-derived products are needed. Integrating sludge management into broader sustainability frameworks, such as the EU's Green Deal or HELCOM's Baltic Sea Action Plan, could provide the necessary policy support to encourage innovation and adoption. Efforts should be made to launch joint projects among the different institutions across the Baltic Sea region to demonstrate the environmental and economical benefits of municipal sludge valorization.

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Sewage sludge biochar and nutrients recovery

Expert article • 3794

Europe's common agricultural policy aims to reduce nutrient losses and foster an efficient management of natural resources, reducing chemical dependency and creating a market for secondary materials. Sewage water and sewage sludge contains considerable amounts of some of the most important nutrients such as nitrogen, potassium, sulphur and phosphorus. The revised EU Urban Waste Water Treatment directive introduces stricter nitrogen and phosphorus discharge limits for bigger sewage plants addressing in this way the challenge of eutrophication and encouraging at the same time nutrient recovery.

Treatment and recycling of sewage sludge poses a challenge for most of European countries today. There are more than two hundred thousand tons of dry matter sewage sludge produced annually in Sweden. About a third of this sludge is recycled through spreading on arable land. The rest is usually used as covering material without nutrient recovery causing a risk for eutrophication and climate change. There is currently a risk that sludge use on arable land might be banned at the same time as the requirement for phosphorus recycling is introduced. Biochar production from sewage sludge through pyrolysis might be a good alternative. This technique shows positive effects regarding reduction of PFAS, microplastics, and pharmaceutical residues as well as climate benefits including reduced transportation, decreased emissions of methane and nitrous oxide, and possible stabilization of carbon in the soil, thereby providing a carbon sink effect.

Our analysis of the business case for pyrolysis of sewage sludge for wastewater companies identifies a series of current challenges that need to be addressed for the technology to realize its full potential.

Sludge biochar is a cleaner product than sludge when it comes to PFAS, pharmaceuticals, heavy metals, and microplastics. However, the impact of sludge biochar on soil and the availability of nutrients over time needs further investigation. The market is thus demanding evidence, and currently, there is a lack of willingness to pay. Moreover, the regulatory framework is complex and unclear. New regulations are being developed, increasing the uncertainty regarding the marketing of sewage sludge biochar.

The assessment of the economics of the business model is linked to the uncertainties surrounding both the production plants costs and the potential sizes of revenues. Operational cost must go down and waste heat recovery needs to be ensured. The market for carbon sinks connected to sewage sludge biochar is in its initial phase and revenues therefore also uncertain. There are some full-scale facilities in Denmark, and a first full-scale facility is currently being built in Sweden but pyrolysis technology still needs further development both considering process and maintenance costs as well as stability of the product quality.

These challenges could be overcome through the development of supporting structures for research, technological development, product certification and business model innovation.

Particularly important research fields include agronomy and material chemistry to describe the effects of sludge biochar in agricultural soils, as well as sludge biochar use and its role as carbon storage in a life cycle context. Funding is therefore required for test beds and research.

Each new sludge pyrolysis facility can contribute to technological development, but the entity making the investment also assumes financial risks. Support for business development, innovation and investment are needed for reducing the financial risk of water and wastewater organizations.

Sewage sludge biochar, as a potential product for fertilization and carbon storage, competes with many other proven and cost-effective products in the market. Therefore, it is crucial that future sludge biochar sellers can guarantee the value of their products, for example, through certifications.

In conclusion, the transition to sewage sludge biochar represents a significant opportunity for sustainable nutrient recovery and carbon storage. To realize its full potential, we must prioritize the development of robust supporting structures that facilitate research, technological innovation, and effective product certification. By investing in these areas, we can overcome the existing challenges, enhance market acceptance, and ensure that sewage sludge biochar becomes a viable alternative in agricultural practices. Collaboration among stakeholders, including policymakers, researchers, and industry leaders, is essential to create a clear regulatory framework and secure the necessary funding. Together, we can pave the way for a greener future that maximizes the value of our natural resources while addressing pressing environmental concerns.

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Water as a crucial nutrient carrier in Baltic Sea Region

Expert article • 3795

In the Baltic Sea region, water plays a crucial role as a nutrient carrier, influencing both the ecosystem and the health of marine life. The Baltic Sea, being a semi-enclosed and shallow body of water, experiences unique dynamics related to nutrient cycling. This means that sustainable nutrient management in this area is not possible without the development and implementation of integrated water resources management plans and strategies at various levels: local, regional and international.

A key concern in the Baltic Sea region is eutrophication, which occurs when excess nutrients (especially nitrogen and phosphorus) cause an overgrowth of algae. This leads to algal blooms, which consume oxygen and create dead zones where marine life cannot survive. Next to surface runoff, mainly from agricultural areas, insufficiently treated sewage is a major source of eutrophication. Wastewater treatment plants (WWTPs), where the main resource is water, especially those that are outdated or underperforming, can be a significant source of nutrient pollution if they discharge untreated or partially treated water. Therefore, WWTPs should be supported in improving management methods and implementing highly effective methods of removing pollutants, including nutrient removal agents, before municipal sewage is discharged into the environment. In addition to the increasingly stringent legal requirements, such as Regulation No. 741 of the European Commission (EU 2020/741) on minimum requirements for water reuse for agricultural irrigation purposes, it is important to create various opportunities for implementing the assumptions of the circular economy (CE) in these enterprises. One of the possibilities is to use sewage treatment methods that allow for controlling the content of nutrients in the treated sewage, which can then be directed to agricultural irrigation. Research in this area is being carried out as part of an international project "Closing local water circuits by recirculation nutrients and water and using them in nature" (ReNutriWater) that is co-financed by European Regional Development Fund (ERDF), as a part of Interreg Baltic Sea Region fund. Thanks to the controlled content of nitrogen and phosphorus in the reclaimed water, it can be treated as 'fertiliser water'. This is a new approach to the topic of water recovery from sewage and its management. This is also in line with the CE idea in which raw materials (in this case water and fertiliser resources) are to be retained in the economy for as long as possible and the amount of waste generated is minimised. There are a number of benefits to this approach to municipal wastewater treatment, including:

- Instead of relying solely on synthetic fertilisers, controlled reclaimed water can provide a sustainable, natural source of nitrogen and phosphorus. This reduces the need for chemical fertilisers, which are energy-intensive to produce and can contribute to pollution if overused.
- By recycling nutrients from wastewater, reclaimed water helps close the nutrient loop, transforming potential waste into a valuable resource for agriculture and thus supporting CE policies in the Baltic Sea Region.
- There are also added values for farmers themselves using reclaimed water - they can benefit financially from using reclaimed water as fertiliser, since it can reduce their dependency on commercial fertilisers.
- By providing controlled levels of these nutrients through reclaimed water, crops can grow healthier and stronger. This is especially beneficial for crops that need a consistent supply of these nutrients.
- Using reclaimed water for irrigation is a way to manage water use more efficiently and in sustainable way. It helps ensure that water used for agriculture is treated and reused, contributing to overall water sustainability.
- Reclaimed water often contains organic materials, which can improve soil structure, water retention, and microbial activity. This can enhance soil fertility over time and help maintain healthy soil for future crops, which is also important topic in the Europe and Baltic Sea region.

In summary, using reclaimed water as "fertiliser water" with controlled nitrogen and phosphorus levels can offer multiple benefits, including sustainable agricultural practices, cost savings, enhanced crop growth, reduced environmental pollution, and improved water conservation. It represents a valuable tool for promoting more circular, resource-efficient systems in agriculture, supporting both economic and ecological sustainability. Therefore, it can be concluded that water is the most important nutrient carrier in the Baltic Sea Region.

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Reed – From shore to store

Expert article • 3796

Reed beds have expanded significantly along the Baltic Sea's coastline due to changes in land use, such as the decline of traditional grazing, and excess nutrients runoff from agriculture and forestry. While reeds play an essential role in stabilizing sediments and preventing erosion, their unchecked growth has contributed to reduced water flow and lower biodiversity. However, these dense reed beds also function as natural nutrient sinks, containing substantial amounts of nitrogen and phosphorus.

Nutrient removal through reed harvesting

Harvesting reeds provides an effective way to remove excess nutrients from coastal ecosystems. Research shows that one hectare of summer reed can absorb 5–10 kg of phosphorus and 50–100 kg of nitrogen, while winter harvest removes approximately one-tenth of the amount of nutrients. If properly harvested and utilized, these nutrients can be repurposed instead of entering the water system, where they would contribute to eutrophication and algal blooms.

To maximize nutrient removal, harvesting should be completed by mid-August before nutrients start accumulating in the rhizomes for the next growing season. Late-summer mowing removes more biomass and associated nutrients, while early-summer cutting significantly suppresses regrowth. Each reed harvest must be carefully planned, ensuring that rare species habitats, bird-nesting periods and fish spawning seasons are considered to minimize ecological disruption.

Large-scale impact on nutrient recirculation

Projects such as BalticReed, led by the John Nurminen Foundation, demonstrate the potential for large-scale reed harvesting to improve water quality while creating valuable biomass resources. Research has indicated that if reeds were systematically harvested from 10,000 hectares 50 –100 tons of phosphorus and 500–1000 tons of nitrogen could be removed, significantly reducing nutrient pollution in the Baltic Sea.

Beyond water purification, sustainable reed harvesting has broader ecological and economic benefits. Removal of reed may improve water flow in shallow coastal bays, and may prevent excessive organic matter accumulation, which accelerates habitat overgrowth. In addition, the harvested biomass provides opportunities for industries seeking alternative raw materials, reducing reliance on traditional agricultural or forest-based biomass.

Sustainable utilization of harvested reed

The biomass from harvested reeds has a wide range of sustainable applications that contribute to nutrient recycling. One important use is as green manure and for soil enrichment, where reeds can be composted or processed into organic soil amendments, thereby returning valuable nutrients to agricultural land. Reed also may play a role in mulching and erosion control. When used as a protective mulch layer, it can enhance soil structure and reduce water loss.

Reed biomass can also be converted into biogas, offering a renewable energy source while repurposing nutrients. Early summer reed, when still soft, can be used as a supplementary feed for cattle.

Challenges and best practices

For effective nutrient recirculation, it is crucial to collect harvested reed from the water and shoreline promptly. If left to decompose, the reeds would release nutrients back into the ecosystem, negating the benefits of harvesting. Additionally, improper cutting techniques—such as mowing too early or disturbing sediments—can lead to nutrient resuspension, undermining the positive environmental impact.

When reeds are cut in early summer, the nutrients stored in the root system may be released back into the water through stems that are cut below the waterline. To prevent this, it is advisable to schedule the cutting for late summer or ensure that cuts are made above the water surface. In shallow waters, using heavy mowing machinery can disturb the bottom sediments, which may cause turbidity and release nutrients from the sediment into the water.

To maximize the benefits of reed harvesting, several best practices should be followed. First, cutting should be timed for late summer to optimize nutrient removal. Additionally, careful planning of the harvesting location and machinery is essential to avoid disturbing sediments and causing nutrient resuspension. All harvested material should be collected to prevent emissions resulting from decomposition. Finally, exploring diverse applications for the harvested biomass is key to promoting a circular economy.

Conclusion

Reed harvesting presents an opportunity to recirculate nutrients, reduce eutrophication, and promote sustainable biomass use. With careful planning, reeds can be transformed from an ecological challenge into a valuable resource, helping to restore the Baltic Sea while supporting a circular bioeconomy. Sustainable reed management is essential to balance environmental conservation with economic benefits, making it a key component of future nutrient recycling efforts. By implementing well-managed harvesting strategies and supporting innovative uses of reed biomass, we can turn an environmental issue into a solution for healthier coastal ecosystems and sustainable industries.

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JULIA LANGE & MICHAEL STÖCKLER

Harnessing algae to save the Baltic Sea

Expert article • 3797

Eutrophication continues to choke the Baltic Sea as excess nutrients from agriculture fuel harmful algal blooms. But a wave of EU-funded projects is fighting back and transforming algae into a powerful tool to clean the water, create sustainable products, and build a blue bioeconomy.

It is no secret that the Baltic Sea suffers from eutrophication, a process in which excessive nutrients accumulate in the sea, leading to algal blooms that reduce light levels in the water, and ultimately deplete oxygen and harm marine life. Right now, the agriculture industry is the prime culprit, releasing large quantities of phosphorous and nitrogen into this stretch of water, largely in the form of surface run-off, which is enormously difficult to manage and control.

Help has been on hand from the Helsinki Convention (HELCOM), which keeps track of Baltic Sea health and implements environment policies via its Baltic Sea Action Plan - yet problems persist. In its latest 'State of the Baltic Sea 2023' publication, HELCOM simply reports: 'The state of the Baltic Sea ecosystem has not improved' and also outlines how the problem is worsened by climate change.

However, numerous European Union-funded projects are now also tackling the issues head on. As part of these initiatives, scientists with backgrounds in algae research are working with industry to reduce industrial waste streams, and develop and market algae-based products, and eventually bring an end to eutrophication.

An algae economy

Julia Lange is the Coordinator of Germany's Innovation Cluster, 'Bioeconomy at Marine Sites' at Kiel University, which currently funds 30 blue bio-economy projects, finding ways to make more of micro- and macroalgae. "We're building a circular, sustainable economy that uses resources from the sea and other water bodies to create sustainable biomass for algae-based products," she highlights.

She is also involved in the EU-funded project, LOCALITY, brings industry players together to deliver algae-based products, including human food, animal feed, textile dyes and ingredients for medicines, to the marketplace. As part of this, the LOCALITY project members are working with macroalgae -seaweeds - grown and farmed in the Baltic Sea. "If we can take excess phosphorous and nitrogen from the water with the help of macroalgae, and then use the algal biomass for, say, human consumption, this will be a win-win for the environment and business," says Lange. "[This] also contributes to a regional food supply, reducing reliance on imports."

In a recent innovation, Lange highlights how teams within her Cluster ingeniously coat seeds with algal biomass and other bioactive components, which then serve as phosphorous- and nitrate-rich fertiliser for the growing plants. "These projects are really helping to restore the Baltic Sea and display potential to transform the traditional agriculture sector," she says.

Michael Stöckler, Senior Innovation Manager of the Food and Bio Cluster Denmark, which helps businesses to accelerate sustainable innovation, also takes part in LOCALITY. He highlights how farming macroalgae in the Baltic Sea spells good news for sea-life. "When you grow algae like this, you're reducing nutrients but also introducing new habitats and shelter for the higher-trophic-level animals, higher up the food chain, such as shrimp and fish," he says. "The higher-trophic fish will also have more food, so in fact, [farming algae] can also help to increase biodiversity in the sea."

Algae innovation

Professor Yagut Allahverdiyeva-Rinne and Dr Sema Sirin, are from Molecular Plant Biology at the University of Turku, Finland, and take part in 'REALM'. The project is pioneering ways to grow microalgae - photosynthetic micro-organisms - in the drain water from Europe's massive, soil-free greenhouses, which is rich in phosphorous and nitrogen. The resulting algal biomass can be transformed into bio-stimulants and products like plant-protection agents and additives for fish feed with the cleaned wastewater then re-used or released to the environment.

Allahverdiyeva-Rinne highlights how Baltic nations and beyond need more biomass, as recently outlined by the European Commission – she is confident microalgae can play a critical role here. "Algae are what we call a third-generation biomass source as we can generate much more biomass [from these organisms] than plants," she says. "So, by growing microalgae, we can use their biomass and also clean the wastewater before it reaches the environment... Also, the necessary technologies for this are relatively mature, so this is going to be important in the short-term."

Allahverdiyeva-Rinne's colleague, Sirin, believes that REALM's decentralised approach suits Finland and other Baltic states in Northern Europe with sparsely distributed population densities. She and colleagues are currently collecting the data from trials at the project's facilities, assessing the feasibility to grow microalgae in this way. If all goes well, operations can eventually be scaled.

"We're dealing with a large amount of water and a continuous discharge, so we really need to make our processes efficient," says Sirin. "Seasons change, discharges changes, but the data from REALM will provide predictability when growing microalgae like this."

And with predictability, comes solid results. "If we can show farmers and growers that producing biomass from greenhouse drain water is not only good for the environment but also provides value and an income, then we have a real solution," she adds.

Rising to challenges

Still, multiple barriers to progress exist. For starters, navigating the complex legal frameworks associated with growing and farming algae on land and in the sea is not always easy. "You know, on the one hand humanity dumps a lot into the oceans, and while we're providing solutions to remove the problems we have to deal with tricky legislation," says Lange. "Still, we're always monitoring the situation, and it is important for algal biomass to be removed in a sustainable way."

Sirin firmly believes that appropriate legislation and ongoing investment will be critical to create a successful algae economy. "Maybe we're not going to solve the Baltic Seas eutrophication problem today," she says. "We're always competing with products from conventional and established industries, but with more investment and [the right] legislation, we will have the opportunity to better-compete and bring new algae-based products to the market."

Beyond legislation, market demand for the products that will be made from the algal biomass remains low. Then there's the hurdle of getting, and keeping, your product into the supermarkets - pain-points that the EU projects are racing to address.

According to Lange, raising public awareness on the massive potential of the algae and the Blue Bioeconomy whilst informing different stakeholders and politicians, is critical. "People need to get to know about the great products, technologies and services that are invented," she says. "We support, for example, education on how to extract a product from the algal biomass and then bring this to market."

However, she is excited to see how algae biomass and products can help to reduce eutrophication in the Baltic Sea. "The results from these projects are so important to communicate what we can do with algae to the outside world, including the public and politicians," she says. "We're now seeing so many passionate people around Europe involved in this topic, which really gives me hope that we can use this momentum and really make a change."

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Closing land-to-sea nutrient gaps by new fertilisers

Expert article • 3798

Significant efforts have been conducted over decades to reduce the loads of nitrogen (N) and phosphorus (P) to the Baltic Sea. Still, eutrophication remains a serious threat to water quality and biodiversity in this important inland ocean, and agricultural activities are the main sources of diffuse nutrient losses via drainage, runoff and erosion. Organic agriculture is acknowledged as one possible solution to reduce such nutrient flows, due to lower surpluses in farm and field level nutrient budgets compared with conventional farming. In most countries around the Baltic Sea, public support for organic production and consumption is well-established and strong. This has contributed to the unique position of Denmark, Estonia, Sweden, and Finland as leading countries in Europe when it comes to the proportions of organic consumption, farmland managed organically, and certified area for wild collection. Refraining from the use of mineral N fertilisers, organic farming systems rely on biological N fixation, and careful utilization of animal manures and other byproducts, often animal-derived. This has prompted a high interest in the development of bio-based fertilisers, to recycle nutrients and organic matter from societal waste. For example, struvite, a phosphate salt, may be precipitated from sewage, and is permitted for use in organic growing. This implies a recycling of valuable nutrients from fork to field and is a promising alternative to triple super phosphate in mineral fertilisers, which is made by acidification of rock phosphate. In general, the productivity per unit of farmland is lower in organic systems, and many stakeholders argue that only high-yielding industrialized agriculture can feed the world. Others have evaluated the food system across the Nordic countries and found that we can feed ourselves in a system with 100% organic agriculture, if our diet is changed to consume mostly vegetable and grain-based food.

In Norway, the Baltic Sea is not dominating the environmental discourse. However, with higher temperatures and stronger rainfall events, eutrophication is a serious challenge in lakes and fjords especially in the eastern and south-west parts of the country. Another relevant difference is the seafood industry, which is much larger than the agricultural sector in Norway. This is the opposite of the situation in other Nordic and in the Baltic countries. The Norwegian seafood industry has a much larger environmental footprint than the agricultural sector, not least because the aquaculture industry has grown extremely fast over the last 20 years, whereas agriculture has stagnated. The economic value of captured wild fish is roughly comparable to the value of raised fish. Cod and halibut are emerging raised species in addition to salmon. The decreasing quota of captured fish is a driver towards better utilization of left-over materials which are rich in both N and P such as fish bones. These are currently poorly utilized but have a high potential as a fertiliser with readily available nutrients for crop plants. The aquaculture industry imports high amounts of materials for fish feed, especially soybean meals. Significant proportions of the nutrients in fish feed are lost to the sea via excretion and feed loss. Whereas this does not directly affect the Baltic Sea, it is not a sustainable way to handle a valuable, scarce resource (P), or to handle reactive N. Efforts are made to reduce feed loss, and collect the sludge, composed of feces and feed loss, from closed systems. Cultivating seaweed to extract nutrients from the sea may be one option to mitigate the nutrient losses, which can also be of interest in the Baltic Sea. Cultivation and harvesting of wild seaweed have attained a large interest in recent years for various applications, not least for production of biostimulants to cope with drought. Brown macroalgae are most relevant for high production of biomass in a Nordic-Baltic context. Some species of brown macroalgae have high concentrations of valuable minerals relevant for complete fertilisers, such as potassium, magnesium, and sulfur. Hence, they complement the fish residues, which are rich in N and P. Marine-derived materials are of high interest as a resource for making fertilisers and to close the nutrient gaps from land to sea, but there are challenges linked to the development of competitive value chains, the salinity of marine materials, and the contents of potentially toxic elements such as cadmium and arsenic (seaweed), zinc (fish sludge), and persistent organic pollutants which tend to accumulate in the sea and in marine organisms.

Whereas Norway could learn a lot from the Baltic region to support the organic sector, which is very small in this country, the Baltic region could possibly learn from the Norwegian efforts to develop sustainable fertiliser products from marine-derived materials.

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Nutrient management in Baltic Sea: Maardu biogas plant

Expert article • 3799

Background

The Baltic Sea encompassed by the Baltic countries and Scandinavia is practically a closed inland sea. Baltic sea conditions have been going into worse for a long period of time. One of the greatest issues for the Baltic Sea has been the incoming nutrition flow from the surrounding countries. Overflow of nitrogen and phosphorous from agricultural farming and manure management have been identified as one of the greatest causes of nutrient leakage and consequently eutrophication of the Baltic Sea.

Surrounding countries have published and initiated several cooperation projects to prevent nutrients from entering the Baltic Sea. Examples of those projects are Sustainable manure and nutrient management (SUMANU-projects) for reduction of nutrient loss in Baltic Sea Region. There are also lots of collaboration companies and communities, like Baltic Sea Action Group, whose target is to improve the condition of the Baltic Sea by bringing businesses and communities together to find ways to reduce the nutrition leakage into the sea.

Sustainable nutrition management in Baltic Sea countries

Like in all areas of Europe in the Baltic and Scandinavian countries, because of farming and meat production, there are areas that produce lots of nutrients. Many agricultural areas are short of phosphorus and therefore need to use artificial fertilizers to fulfill the need to grow the crops.

In Sweden, manure is viewed as a valuable resource, because biogas process reduces its amount while retaining all the nutrients. In Denmark, the legislation has driven the farmers to build biogas plants as for manure treatment before fertilizer utilization as well. This is based on the limitation for animals per hectare and restrictions on nitrogen application to crops.

In Finland, there are different limits for amounts of phosphorus and nitrogen per hectare for different crops. Biggest difference from Denmark is that for example in 2021, Denmark produced 1,724 M kg of pork meat when Finland produced 176 M kg. The area of agricultural land is similar in Denmark and Finland; 2,6 M hectares Denmark and 2,2 in Finland. Because of those numbers, in Finland there has not been so much interest towards manure digestion until 2023. In Finland, the biogas production has concentrated to use source separated food waste and WWTP sludge as feedstocks and origin on biofertilizers.

In Baltic Countries (Estonia, Lithuania and Latvia), there are lots of big farms. Some of them are using biogas plants to produce biofertilizers from the manure, but for source separated food waste, there are so far only very few plants. This is a pity, because food waste is very nutritious and its biogas i.e. energy yield is high, but at the same time, the tide seems to be turning.

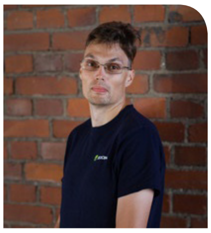
Case Maardu Biogasplant

Maardu Biogas plant is a build biogas operated and owned by EKT Ecobio and build by BioWoima Finland. Production started in 2023. It uses source-separated food waste from households and grocery stores as its feedstock (24,000 tons per year) and produces annually 30 GWh of biomethane. Plant is powered by a hybrid digestion process, where the pretreated and hygiene biowaste is first pump to semi dry plug-flow digester and then to traditional wet-digestion to provide a better gas production. Produced biomethane is used as a traffic fuel for Tallin buses to replace the natural gas.

EKT plant is the first biogas plant in Estonia that uses food waste as feedstock and produces organic fertilizers from it for agricultural purposes. To fulfill the EU fertilizer legislations, all plastic, metals and other non-organic materials are removed in a two-step process. Pretreatment before digestion removes the bags, other bigger non-organic particles and heavy fractions like stones, whereas two-step post-separation by screw presses removes the small particles what are left after the pretreatment.

According to regular inspections by a third party, there have so far been no visible non-organic fractions at the solid digestate. This proves that it is possible to produce organic fertilizers from biowaste streams. Separated liquid material is also used as fertilizer as well.

By using biogas process to treat source separated food waste and other high-nutrient organic waste streams, it is possible to capture and reuse the nutrients in farming in a sustainable way. The biogas process also transforms most of the nitrogen into a more soluble ammonium form, which the plants and crops can absorb faster and more efficiently. This decreases the nutritional leakage from farming into the Baltic Sea, in addition to replacing traditional composting processes (where leakages also occur) by fully closed anaerobic biogas process. In the end of the day, all win: the waste producers, the management sector, and the environment.



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Recycled fertilizers & biogas for Baltic Sea sustainability

Expert article • 3800

In Finland, nearly 20 million tons of livestock manure, about 1.5 million tons of agricultural surplus grass, and a total of over 2 million tons of various organic sludges, waste, and by-products from municipalities and industries are produced annually. The nutrients in these biomass sources are unevenly distributed across Finland, leading to regions with nutrient surpluses and deficits. A breakthrough in efficient nutrient recycling has yet to be achieved, requiring broad collaboration and strong commitment to solving the issue. When properly planned and implemented, nutrient recycling can significantly reduce nutrient emissions into the environment and decrease the use of non-renewable natural resources. Thus, nutrient recycling is a matter of national security and self-sufficiency.

The Baltic Sea, one of the most enclosed and sensitive marine ecosystems in the world, faces significant environmental challenges, largely due to eutrophication. One of the main contributors to this nutrient overload is agricultural runoff. In response, sustainable nutrient management strategies have become a focal point of environmental policy and research in the Baltic Sea Region (BSR), especially the innovative use of recycled fertilizers and biogas. These solutions can close nutrient loops, reduce reliance on synthetic inputs, enable domestic energy production, and support agricultural sustainability and environmental restoration.

Recycled fertilizers, which are derived from waste and side streams such as food waste, manure, sewage sludge, and agricultural residues, are gaining attention as an alternative to traditional synthetic fertilizers. By repurposing waste and side stream materials into carbon- and moderately nutrient-rich fertilizers, recycled fertilizers help close the nutrient loop and reduce the environmental burden of agricultural production. Biogas offers multifaceted benefits and is a true win-win solution: it simultaneously strengthens energy and nutrient self-sufficiency, reduces emissions in agriculture and transportation, and increases the domestic share of production inputs.

The use of recycled fertilizers has several environmental benefits. Organic fertilizers improve soil structure, water retention, and biodiversity while enhancing carbon sequestration—key for sustainable agriculture in the Baltic Sea Region.

It has been estimated that recycled phosphorus could cover 90% and recycled nitrogen more than one-third of Finland's annual plant production needs for phosphorus and nitrogen. Using local side and waste streams can reduce the need for synthetic fertilizers and lower the carbon footprint of fertilization and manure processing emissions.

From an economic perspective, recycled fertilizers provide a cost-effective alternative to conventional fertilizers, especially in regions where waste streams are abundant. Moreover, the production of recycled fertilizers can create new business opportunities and jobs.

While the potential for recycled fertilizers and biogas in sustainable nutrient management is clear, several challenges must be addressed to scale these solutions effectively in the Baltic Sea Region. These include regulatory barriers, logistical, and economic considerations. For instance, there is a need for policies that incentivize the use of recycled fertilizers and support the growth of biogas infrastructure. Additionally, there is a need to ensure that recycled fertilizers meet increasingly stringent quality standards. However, these challenges present opportunities for innovation. Additionally, the development of market incentives, such as subsidies or tax breaks for farmers who use recycled fertilizers, can help accelerate the adoption of these sustainable practices.

Cooperation among countries and industries in the BSR is essential. Finnish Biocycle and Biogas Association is one of the project partners in CiNURGi project, that brings organisations into symbioses to find solutions to recycle nutrient-rich biomasses into safe fertilizers and provides authorities with roadmaps to further facilitate reducing nutrient losses in future. The project aligns with several key regional and European strategies, contributing to sustainability and resource efficiency in BSR.

Sustainable nutrient management in the Baltic Sea Region is crucial to addressing the ongoing problem of eutrophication and protecting the health of this vital ecosystem. Recycled fertilizers and biogas offer innovative, circular solutions that can reduce nutrient pollution, enhance soil fertility, and mitigate climate change. By harnessing local waste streams, the region can create a more sustainable agricultural system that reduces reliance on synthetic fertilizers, improves water quality, and supports the broader goals of environmental and economic sustainability. Cross-border collaboration across sectors and research is key to scaling these solutions and ensuring the Baltic Sea Region remains resilient and vibrant in the long term.

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Digestate management for sustainability

Expert article • 3800

With the approval of the European Green Deal and featured initiatives developed within its framework, increasing importance is devoted to aspects such as efficient resource management and use, the role of renewable energy in promoting energy independence, healthy soils and the implementation of circular economy principles in various sectors. In turn, the HELCOM Regional Nutrient recycling strategy emphasises that nutrient recycling on land and losses to the sea should be improved to reduce the harmful impact on the Baltic Sea.

One sector that impacts nutrient leakage is biogas production, which has been developed for decades as part of sustainable energy and resource management strategies.

Biogas production in the Baltic Sea Region is essential as a source of renewable energy and an effective way to process biological waste. It promotes energy independence, reduces greenhouse gas emissions, and helps process organic waste from agriculture, the food industry, and household waste, thus promoting sustainable resource circulation. However, the biogas production process produces digestate – a nutrient-rich by-product that, if properly managed, can become a valuable resource for improving soil fertility and sustainable agriculture. The high-quality use of digestate helps to effectively close the nutrient cycle, reducing the need for synthetic fertilisers, and significantly reduces environmental pollution, especially in the Baltic Sea region, where excessive nutrient discharge into the waters is a significant ecological problem. Therefore, digestate management and quality assurance are becoming an essential aspect of the region's sustainable development policy.

To ensure effective digestate management, it is crucial to consider several aspects which have an impact on sustainability and the environment:

- composition – in biogas production as feedstock, different organic materials such as agricultural, food, industrial, and sewage sludge are used. It is essential to ensure that feedstock is of proper quality and does not include harmful substances such as heavy metals as they afterwards occur also in the digestate;
- Nutrient leakage and pollution—digestate mismanagement can contaminate soils and water, contribute to eutrophication, and emit greenhouse gases. National legislation determines how to ensure the proper incorporation of digestate into the soil, which must be followed during its storage to avoid soil and air pollution.

However, one of the effective ways to ensure the safe use of digestate is to establish quality assurance systems. The digestate quality assurance system aims to create a framework and requirements for biogas plants that use raw materials in the anaerobic digestion process and for the digestate obtained during the relevant process to ensure its compliance with specific safety and quality indicators, as a result of which the digestate acquires end-of-waste status and can be safely used as fertiliser.

The establishment of a quality assurance system has several objectives:

1. to create a framework and system for the circulation and use of processed nutrient products;
2. to ensure the quality of processed nutrient products;
3. to ensure the traceability of raw materials and the transparency of the raw material chain;
4. to promote compliance with the principles of the circular economy;
5. to increase awareness of processed nutrient products and their quality;
6. to inform the end user about how, where and from which raw materials processed nutrient products are produced.

In several Baltic Sea region countries, digestate quality assurance schemes have already been in place for several years, contributing efficiently to the effective nutrient management in agriculture and landscaping, and they are developed according to the specific country's legislation and needs. Digestate quality assurance systems are in place in the Baltic Sea region in Germany, Finland, Sweden and Estonia. In Latvia, the digestate quality assurance system proposal was developed in the framework of the Interreg Central Baltic programme project "Sustainable biogas", but it is not operative.

However, to enhance digestate sustainability in the Baltic Sea Region, it is essential to develop harmonised standards for digestate quality assessment. This approach would maximise digestate's agricultural benefits while minimising environmental risks. Also, common standards and management policy would change the public perception as misconceptions about digestate safety and effectiveness prevail over its environmental benefits.

The Baltic Sea Region can advance towards more sustainable nutrient management by implementing standardised regulations, improving processing technologies, and fostering cross-border collaboration. Future efforts should focus on bridging policy gaps, encouraging innovation, and ensuring long-term environmental protection.

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The engine of nutrient recycling

Expert article • 3801

The food system consists of various phases and processes, in which a large amount of nutrients flow along with raw materials and products. Primary production acts as the engine of nutrient recycling in the system, as it recycles leakages from both its own and other phases back into new growth. In the short cycle of primary production, animals utilise feed in the fields, and some of the nutrients contained in the feed end up in manure and again in the production of new feed. Feed-grade by products from food industry are used for feeding, and if the by-products are not suitable for feed, they can be recycled into plant production through biogas plant, or if medium risk materials, through rendering process. In addition, spoiled feed from primary production, ineligible food from processing and retail, as well as food waste from food services and consumers should be recovered as accurately and cleanly as possible, so that the valuable nutrients and organic matter it contains can be returned to the system, e.g. through biogas production.

Meat production is often seen as a water pollution problem rather than the engine of nutrient recycling. The unnecessarily high phosphorus fertilization of recent decades due to the lack of knowledge is still challenging today's farmers in the form of high phosphorus levels in certain fields, posing a risk of water pollution. Increased rainfall due to climate change further challenges this. However, manure is also a valuable fertilizer with multiple positive effects on the environment. In addition to the main nutrients, it contains organic matter and trace elements that support soil fertility and biodiversity. Indeed, well-maintained arable land produces high yields and reduces the risk of water pollution.

Sustainable nutrient recycling requires consideration of both regional and local conditions and the various aspects of sustainability. For example, methane emissions are formed during the storage of manure, which can largely be avoided if the manure is treated fresh in a biogas plant. On the other hand, mixing, handling and non-optimal spreading methods of manure or digestate can cause ammonia emissions or nutrient runoff, so from the perspective of overall sustainability, all phases from animal feeding, manure storage, processing, and application to the field must be properly managed. Manure processing is not mandatory; manure is beneficial for fields as it is when used properly. At the farm level, low-tech solutions can also significantly improve both nutrient utilization and nutrient self-sufficiency.

Biogas plants are often proposed as a simple solution to nutrient surplus in the areas of intensive livestock production. However, from the perspective of nutrient recycling, the biogas production phase is only a throughput process, where the mass remains almost the same and the total amount of nutrients does not change. Nutrients do not disappear, but the proportion of plant available nitrogen increases – both important aspects of nutrient recycling. So, if the target is to solve a regional nutrient surplus, a digestate processing phase is required after the biogas process, where the nutrients are separated into more concentrated end-products. These products can be transported more cost-effectively over longer distances than raw manure and digestate, thus enabling the transfer of surplus phosphorus to crop-producing areas to replace chemical fertilisers. If carefully planned and managed, the combination of biogas production and digestate processing can significantly reduce greenhouse gas emissions from meat production and the need for imported fertilisers, thereby increasing nutrient self-sufficiency in primary production, improving security of food supply, and reducing the risk of water pollution.

From the perspective of the environmental sustainability of the food system, it is important that regulations support the sustainable use and recycling of nutrients in primary production. Regional and farm-specific differences must be considered, as the same solutions are not suitable everywhere and for everyone. It must be ensured that, e.g., biogas investments also consider the processing of digestate and support the adoption of processing technologies and new innovations. There must also be room for farm-scale low-tech solutions. Highlighting the positive effects of various measures encourages actors to implement them.

Atria, as a leading food company in Northern Europe, has actively collaborated with research institutes, universities, foundations and other stakeholders and companies, and is participating in the current Finnish government's Archipelago Sea program, aiming to promote the sustainable use and recycling of nutrients both in its own operations and in supply chains. Atria is currently building a biogas plant producing liquefied biogas and recycled nutrients from manure and food industry by-products near its Nurmo slaughterhouse in collaboration with Suomen Lantakaasu Oy.

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Bio-based fertilizers: A practical approach towards circular economy

Expert article • 3802

Introduction

Efficient nutrient management reduces eutrophication in the Baltic Sea region through buffer zones, controlled drainage, and cover crops that limit runoff. Excessive synthetic fertilizer use leads to phosphorus and nitrogen pollution, harming water ecosystems. Bio-based fertilizers (BBFs), derived from organic waste, recycle nutrients and offer a sustainable alternative to conventional fertilizers. Their use decreases reliance on imported phosphate rock, stabilizes costs, and strengthens farmers' resilience.

Replacing synthetic nitrogen fertilizers lowers agriculture's carbon footprint by reducing dependence on the energy-intensive Haber-Bosch process. Struvite and digestate-based fertilizers provide slow-release phosphorus and organic matter, improving soil fertility while reducing nutrient leaching. Biochar enhances water retention and carbon sequestration. However, BBF adoption requires research on nutrient efficiency, regulatory clarity, and financial incentives.

Integrating BBFs with precision agriculture improves nutrient uptake and reduces waste. Variable rate application (VRA), nutrient mapping, and sensor-based monitoring optimize BBF distribution, minimizing losses and increasing yields. The EU Farm-to-Fork Strategy supports these practices to reduce synthetic fertilizer use and promote organic alternatives.

Production technologies and applications

BBF production varies in duration, composition, and environmental impact. Fermentation takes 2–4 weeks, yielding digestate rich in nitrogen and organic matter, often used in biogas plants. Microelement extraction, completed in 24–48 hours, enhances plant micronutrient uptake using algae and fish residues. Microbial enrichment, lasting days to weeks, introduces phosphorus-solubilizing bacteria (PSB) and nitrogen-fixing microbes to improve nutrient availability in phosphorus-deficient soils.

Biochar enhances soil structure, retains water, and sequesters carbon. It reduces nitrogen leaching and extends fertilizer efficiency. Composting, lasting 4–8 weeks, supports microbial diversity and organic matter retention, making it a scalable solution for farms processing agricultural residues. Struvite recovery from wastewater provides slow-release phosphorus, reducing dependence on mined phosphate rock. Biodisinfection, conducted at 30–40°C for several days to weeks, introduces volatile fatty acids and antimicrobial compounds to suppress pathogens and enrich organic matter.

Scaling BBF production requires a steady supply of organic residues, including manure, crop waste, and food processing by-products. The Baltic Sea region generates large volumes of these materials, but infrastructure differences affect availability. Strengthening cooperation between BBF producers and waste sectors can improve nutrient recycling, reduce reliance on imported fertilizers, and support local economies. Efficient supply chains and optimized feedstock use will promote BBF adoption and reinforce circular economy principles.

Implementation in the Baltic Sea Region

BBF adoption varies across the Baltic region. Finland's subsidies, covering up to 30% of production costs, have accelerated industrial-scale use. Germany and Denmark, benefiting from strict fertilizer limits and circular economy policies, lead in implementation. Poland, Lithuania, and Latvia face slower adoption due to regulatory delays, limited infrastructure, and seasonal feedstock variability. Sweden promotes biochar through tax deductions and government trials in cereal production. Estonia and Lithuania focus on digestate-based fertilizers, integrating biogas production with nutrient recycling. Germany has expanded struvite recovery, particularly in Hamburg, as part of circular economy initiatives.

Despite regulatory improvements, adoption remains slow due to inconsistent policies, complex certification, and limited farmer outreach. Expanding subsidies, technical support, and demonstration projects could accelerate adoption. Aligning national regulations with EU directives would facilitate market growth and cross-border cooperation.

Economic and policy framework

BBF economic feasibility depends on production scale, feedstock availability, and policy support. Fermentation and biodisinfection benefit from biogas revenue, offsetting costs. Composting is a low-cost, scalable option supported by subsidies. Biochar production requires high initial investment but provides long-term soil health benefits. Struvite recovery is cheaper than phosphate rock but demands advanced processing infrastructure. Regulatory inconsistencies and lengthy approval processes hinder market expansion.

Strengthening public-private partnerships, improving certification processes, and standardizing BBF quality will increase adoption. Expanding financial incentives and reducing investment risks will support farmers transitioning to BBFs, making them a viable alternative to synthetic fertilizers.

The EU Fertilizing Products Regulation (EU 2019/1009) sets certification standards, ensuring BBF safety and limiting heavy metal content. The EU Farm-to-Fork Strategy aims to cut nutrient losses and fertilizer use, aligning with HELCOM environmental objectives. However, regulatory inconsistencies, high production costs, and infrastructure limitations still slow BBF market expansion. Coordinated policies, financial support, and risk-sharing mechanisms can improve adoption.

Stakeholder recommendations

Policy and regulation

- Set clear targets to reduce synthetic fertilizer use.
- Expand financial incentives to improve BBF competitiveness.
- Harmonize HELCOM and EU regulatory frameworks.

Agricultural sector

- Implement precision agriculture (GPS guidance, nutrient mapping) to optimize BBF efficiency and minimize runoff.
- Provide training on BBF benefits and application methods.

Industry and innovation

- Standardize BBF quality protocols, specifying nutrient content and labeling.
- Enhance microbial enrichment with PSB and nitrogen-fixing microbes.
- Increase regional organic waste use in BBF production.
- Strengthen public-private partnerships to scale BBF manufacturing.

Long-term research should evaluate BBFs' effects on soil microbial balance and nutrient cycling. Continuous use influences microbial composition, organic matter turnover, and nutrient bioavailability. Understanding these dynamics is essential for soil fertility, particularly in intensive farming.

Consumer education

- Promote awareness campaigns on BBF environmental and nutritional benefits.

Enhancing BBF efficiency, adoption, and policy integration

Research priorities

- Soil and microbial dynamics - Assess BBF effects on microbial diversity, nutrient cycling, and carbon sequestration in phosphorus-deficient soils.
- Nutrient retention - Compare BBFs and synthetic fertilizers in nutrient leaching, focusing on biochar's role in retention and carbon sequestration.
- Lifecycle and economics - Evaluate production emissions, energy use, cost-effectiveness, and long-term soil benefits of BBFs.
- Regulation and market growth - Simplify certification, trade, and policy alignment under EU and HELCOM frameworks while improving financial models.
- Agricultural integration - Examine BBF interactions with pesticides, herbicides, and irrigation for better nutrient and pest management.
- Scaling production - Optimize feedstocks and processing to improve efficiency, reduce waste, and ensure consistent quality.

Strategies for widespread adoption

- Strengthen public-private partnerships to drive market integration.
- Expand financial incentives to support BBF development.
- Align EU and national regulations to facilitate adoption.
- Advance microbial enrichment and precision application for improved nutrient efficiency.
- Address infrastructure gaps and promote innovation in BBF production.
- Provide financial and technical support to farmers for a smoother transition to BBFs.

Final remarks

The EU Farm-to-Fork Strategy's success relies on collaboration between policymakers, industry, and farmers. Advancing research on microbial enrichment and BBF interactions will enhance nutrient efficiency and sustainability. Coordinated regulations, financial support, and policy alignment will accelerate circular agriculture, improving soil productivity and biodiversity. Clear policies, optimized nutrient application, and strategic organic waste use will integrate BBFs into sustainable European agriculture. Expanding financial support, increasing research efforts, and fostering public-private partnerships will be key to market growth and long-term environmental benefits.

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Biobased resources as feedstock for the bioeconomy

Expert article • 3803

The Earth receives 1366 W/m2 (2,500,000 EJ) of solar radiation per year, of which 0.25% is converted into usable biomass by the process of photosynthesis. Around 175,000 million tons of carbon, equivalent to about 300,000 million tons of biomass, are sequestered by the Earth's vegetation each year.

Given that carbon (C) is the main building block of most of the chemical compounds we produce and consume, our economy could be described as a carbon economy. Before humanity discovered fossil oil, coal, gas and uranium and learnt to put them to use, biomass met all human needs for food, energy and materials. Today, a return to the use of renewable C from biobased resources is necessary to avoid the further exploitation of limited fossil resources, the use of which is the main contributor to increasing atmospheric CO_2 concentrations and the subsequent global warming effect.

Both, biobased and carbonaceous fossil resources are derived from biomass that has been built through the process of photosynthesis. In this process, plants and algae take up CO_2 using energy from the sun. They convert light into chemical energy by incorporating C into their organisms. The C bound in fossil fuels was absorbed from atmospheric CO_2 millions of years ago. Biobased resources, on the other hand, consist of biomass that has grown much more recently. Here, the CO_2 is removed from and returned to the atmosphere within a short time period of 1 to <100 years.

This "CO_2 fixation" lasts as long as the biomass is used as material, e.g. in building materials, or incorporated into soil organic matter. If the biomass is used for energy, the same amount of CO_2 is returned to the atmosphere as was fixed in the photosynthesis process. Using biomass instead of fossil fuels keeps fossil C in the ground, thus mitigating climate change. The bioeconomy applies these processes and uses biobased resources as its renewable feedstock.

The bioeconomy is an operational, cross-sectoral approach to a circular and sustainable economy. The most recent description of the bioeconomy comes from the International Advisory Council of the Global Bioeconomy Summit (IACGB, 2024): "The bioeconomy is the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy. The bioeconomy is not a static notion and its meaning is continually evolving." The last sentence points out that the bioeconomy is a dynamic field. With its great potential to provide solutions to pressing societal challenges, such as climate change mitigation, healthy food supply and sustainable use of natural resources, the bioeconomy is emerging as a global concept. As of 2024, more than 60 countries had dedicated or related bioeconomy strategies.

Biobased resources are all resources containing non-fossil, organic C recently derived from living plants, animals, algae, microorganisms or organic residues and waste streams. Together they are often referred to as 'biomass'. This can be both edible biomass (e.g. rich in protein, starch, sugar or oils) or non-edible lignocellulosic biomass from dedicated crop production, residues and organic wastes. Early potential analyses have shown that, beyond the needs of food and feed production, lignocellulosic biomass in particular would be available in quantities even greater than global energy consumption. However, limits to the sustainable supply of biomass and competition with food production land and biodiversity are often cited as criticisms of bioeconomic development. Biomass is an almost ubiquitous resource, but it is widely distributed. This is a major difference from fossil resources, which are mostly point sources. Biobased resources are distributed not only in space but also in time, with peaks during harvest periods, and can vary in quality. Regional availability also depends strongly on site conditions that determine the physical potential for biomass growth, productivity and production intensity, as well as the infrastructure for harvesting, processing, storing and transporting the biomass. This makes a reliable estimate of the technical availability of sustainably produced biomass challenging.

In line with sustainability goals, the bioeconomy employs approaches such as the food-first principle, cascading use of biomass, life-cycle thinking and multifunctionality, optimizing energy and nutrient use, conserving biodiversity, promoting soil health and agroecological practices. The optional allocation of biomass to different uses is guided by the prioritization of healthy food supply and the cascading principle, i.e. the continuous use of resources for various purposes, optimally through different material reuse phases to preserve the 'added value' of products for as long as possible. Multifunctionality involves the integrated production of biomass for food, feed, material and energy uses in sustainable agriculture and forestry, together with the provision of ecosystem services such as soil carbon sequestration, soil and landscape regeneration and pollination services, to name but a few.

Biorefinery approaches apply cascading use and circularity and are important to exploit biobased resources efficiently. Biorefining is an integrative concept for the sustainable processing of biobased resources into a range of marketable, value-added products, including chemicals, materials, fuels and energy, operated with the aim of full utilization of biomass. An important example of the application of biorefinery technologies is the recycling of plant nutrients during the processing of biomass or from its products or from organic wastes. The resulting 'biobased' or 'recycling' fertilizers close regional nutrient cycles and can replace a major part of synthetically produced nitrogen (N) or fossil-based phosphorus (P) fertilizers. Replacing synthetic fertilizer by recycling fertilizer reduces CO_2 emissions, as the production of synthetic N fertilizer is associated with annual emissions of 310 million tons of CO_2. The use of recycled N and P fertilizers also reduces the use of fossil resources and imports, supporting regional and reliable supply chains and the resilience of agricultural systems.

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Cooperation on nutrient management in the BSR

Expert article • 3804

Working together on sustainable nutrient management has a long history in the Baltic Sea Region (BSR). The countries of BSR are small, and it's been clear for a while that no single country can solve the sea pollution problem alone. Already the worst has been avoided, and trends are towards improving conditions in many places. So, there is still a need for intensive cooperation.

The Helsinki Commission (HELCOM) was set up 50 years ago to make this cooperation a long-term commitment. It serves as a platform for regional policymaking. In 2009, the EU Strategy for the Baltic Sea Region (EUSBSR) started, making cooperation even stronger, more inclusive, and open. The EUSBSR aims to cut down on overlapping work among existing networks and organizations, improve information flow, and bring stakeholders together.

Nutri is one of the Policy Areas under the EUSBSR, coordinated by the Centre for Economic Development, Transport and the Environment for Southwest Finland and State Water Enterprise Polish Waters and funded by Interreg Baltic Sea Region -programme. Its goal is to reduce nutrient inputs to the sea and promote nutrient recycling. Nutri helps implement HELCOM's Baltic Sea Action Plan. While HELCOM handles regional policymaking, Nutri focuses on supportive activities like working with projects where HELCOM isn't a partner and linking them to regional policies. This way, results from ongoing projects can feed into regional policies through cooperation facilitated by Nutri and other EUSBSR Policy Areas. Nutri and HELCOM have a well-established cooperation, with both observing each other's meetings.

In addition, many local, regional, national and Baltic Sea-wide organisations such as Union of Baltic Cities, Coalition Clean Baltic, Race for the Baltic and WWF Baltic Sea programme also actively develop nutrient management towards more sustainable practices.

Cooperation with remote parts of the BSR

Some parts of the Baltic Sea catchment area belong to countries that are beyond Interreg Baltic Sea Region -programme's and HELCOM's usual operational area. Due to the Russian Federation's unprovoked and illegal war of aggression against Ukraine, an observer state to HELCOM, all regular meetings of HELCOM bodies and project groups involving the Russian Federation under the HELCOM umbrella are currently postponed. This strategic pause does not mean a cessation of HELCOM activities. While small parts of Norway, Ukraine, Czechia, and Slovakia fall within the catchment area, their level of cooperation within the Baltic Sea Region framework remains limited.

However, engaging with politically cooperative countries that are not HELCOM Contracting Parties remains important. Through collaboration and joint projects, EU countries in the Baltic Sea Region can support Ukraine's efforts to align with EU environmental standards and avoid past mistakes. At the same time, broader engagement across the region can strengthen efforts to reduce nutrient pollution and improve water quality.

EUSBSR has facilitated cooperation with Ukraine by organizing events where Ukrainian stakeholders have voice their needs and challenges and networked with potential partners. Nutri's Polish coordinator also joined as a partner to Clean Baltic Source project, funded by the Swedish Institute. It begun a concrete cooperation on wastewater issues between stakeholders from the Lviv region and the BSR. The project helped Ukrainian municipalities and wastewater treatment operators get information from Swedish and Polish organizations. The established cooperation continues through other projects. Rebuilding efforts of Ukraine have already begun, and countries are setting up concrete infrastructure investment plans. Rebuilding back better can also improve nutrient management.

Capitalization of project results

The idea behind cooperating with projects is to extend project life cycles and bring attention to ongoing projects. Nutri and other Policy Areas facilitate idea generation in topics relevant to their goals and help new stakeholders find partners in the region. Als organisation of joint events with several projects is more effective.

The Annual Forum of the EUSBSR is a hub for projects to showcase their activities through the Networking Village and workshops. Online events like PA Nutri Talks provide open and inclusive opportunities to discuss specific topics and present projects and policies from around the BSR.

Some topics like nutrient recycling is still research heavy. There is a need to activate also other stakeholders like farmer unions to project and cooperation work. This will be a future focus for Nutri.

Future developments

PA Nutri plans to start two reference groups. One group will focus on implementation of national actions in HELCOM's BSAP related to nutrient recycling, and the second on wastewater treatment. The groups will facilitate experience exchange between countries and stakeholders and help identify needs for joint projects or other activities.

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The nutrient management governance gap in the Baltic Sea Region

Expert article • 3805

The Baltic Sea is an interesting case that reveals the complexity of effectively regulating nutrient loss to water bodies. This is especially apparent since the entry of the EU into the Baltic scene. The Helsinki Convention (HELCOM), set up in 1974 to protect the Baltic Sea from pollution, has been essentially advisory since its start, which has resulted in varied levels of positive impact. The recent addition of complex and competing directives by the EU is making compliance and enforcement even more difficult.

The Baltic Sea has a residence time of 25 to 40 years, making it particularly sensitive to environmental changes. As a large transitional inland brackish water body, it supports only a limited mix of marine and freshwater species. Its deeper layers are saltier and separated from surface waters by halocline, resulting in anoxic conditions in the deeper zones. Oxygen renewal at these depths only occurs during rare major North Sea storms that push oxygenated seawater over the shallow sill in the Danish and Oresund Straits. The surrounding population of over 85 million people has significantly impacted the Baltic Sea through overfishing, especially of cod, sprat, and herring, along with fertilizer pollution especially between the 1950s and 1980s, sewage and industrial effluents, ammonia and nitrate from the atmosphere, heavy shipping activity, and remnants from many military operations.

The Baltic coastal waters are phosphorus (P)-limited, while the open sea is nitrogen (N)-limited for most of the year. Each summer, blooms of P-limited cyanobacteria (mainly *Nodularia* and *Aphanizomenon*) occur, which can fix atmospheric N—adding upwards of 400,000 tons of N annually, close to the riverine load from farms and cities. Despite reductions in N and P emissions since the 1980s, legacy P (stored P from historic overloading) derived from bottom sediments and the drainage basin continues to feed eutrophication. Combined with the sea's long water residence time, this sustains poor water quality. Coastal hotspots, especially in the south, still receive high nutrient loads from agriculture and urban areas.

HELCOM produces a nutrient management action plan specifying annual discharge quotas for each member country to prevent eutrophication. But HELCOM remains only an advisory body to the 8 EU member states plus Russia. Enforcement is dependent on national legislation. Compliance with the EU Urban Wastewater Treatment and the Nitrates Directives (stipulating a maximum of 170 kg N/ha/yr in N-sensitive zones) have reduced some of the N and P discharges from point sources and N from diffuse agricultural sources. Since 2009, the EU has taken a regional approach to nutrient management based on drainage basin nutrient inputs, governed by the Water Framework Directive (WFD). The WFD is an impressive blueprint for action but has had major implementation challenges across the EU regarding access and costs to obtain the necessary comprehensive data, let alone the ensuing measures required. The deadline for the individual drainage basin action plans was 2015. This was extended to 2027 due to slow compliance.

Other recent interventions are the EU Green Deal, Farm to Fork (F2F) and Mission Starfish (MS) strategies. MS, aims to protect ocean and water bodies by 2030 (base year 2012-2015), reducing total water abstraction by 50%, including groundwater by 20%, undamming 30% of Europe's rivers, reducing nutrient losses by 50%, and 100% of urban wastewater receiving tertiary treatment (ie P removal). F2F as part of the Green Deal lays up agricultural targets by 2030 to reduce nutrient losses by 50% resulting in at least 20% reduction in fertilizer use. To implement the F2F strategy the reformed Common Agriculture Policy (CAP) is the vehicle of choice. With a budget of around 1 billion Euros per week, the CAP is an instrument that has the potential to accomplish most agricultural reforms. But there is little evidence that this edifice of farm subsidies will be taking on these ambitious targets to protect drainage basins from nutrient overloading. The Nitrates Directive regulates application of N from animal manure to fields but completely ignores P which enters water bodies as runoff. To manage the Baltic Sea, both N and P need to be regulated in an integrated and ratio-based approach.

EU Investments have been made in upgrading Baltic region urban wastewater treatment plants in the new EU member states. But all in all, the improvements in nutrient emissions have been limited, mainly because the diffuse agricultural emissions have not been monitored and reduction in runoff not enforced. The need to sustainably recycle nutrient flows from plant and animal production systems is still waning. In addition, the EU is not self-sufficient due to its 90% dependence on imported P fertilizers. As a result, the EU has placed P on the Critical Raw Materials List demanding better management and recycling. But how optimistic can we be with the 2027-extended WFD, and the 2030 Mission Starfish and F2F strategies on the horizon, all without adequate monitoring and compliance?

The Baltic Sea will remain a major challenge for the EU to manage. Ideally there is a need to reform HELCOM with its long track record and make the Baltic Sea a special protected area requiring special governance treatment, with implementation and enforcement funding made available from within the EU. This would provide an element of cohesion and inclusiveness, something that is clearly missing at present.

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Our regional strategy for nutrient recycling

Expert article • 3806

Eutrophication – caused by excessive phosphorus and nitrogen inputs from human activities – remains one of the most influential and persistent environmental pressures in the Baltic Sea. It leads to algal blooms, oxygen depletion, and severe disruptions to marine ecosystems and biodiversity, affecting also the ecosystem services these ecosystems provide us. The interactions between eutrophication and climate change create additional risks, many of which are still not fully understood. To address these challenges, the Baltic Marine Environment Protection Commission (HELCOM) developed the Baltic Sea Regional Nutrient Recycling Strategy (2021). This strategy provides a comprehensive set of measures aimed at improving nutrient use efficiency, reducing nutrient losses, and enhancing recycling to keep valuable nutrients in food systems.

Why is the strategy needed?

The HELCOM Baltic Sea Action Plan (BSAP) has guided regional efforts to improve the Baltic Sea's environmental state since 2007 and revised in 2021. HELCOM's 2018 Ministerial meeting recognized the importance of nutrient recycling in tackling eutrophication, enhancing resource efficiency, and supporting climate goals. In related declaration, HELCOM committed to developing a Baltic Sea Regional Nutrient Recycling Strategy that would complement the BSAP, providing a vision and comprehensive set of objectives and measures for sustainable and safe utilization of regionally available nutrients. Finland's HELCOM chairmanship prioritized the strategy, underscoring its dual environmental and economic significance. HELCOM Contracting Parties adopted the strategy in 2021 Ministerial Meeting as one of the action documents associated with the updated Baltic Sea Action Plan.

Vision and objectives of the strategy

The vision of the strategy is that nutrients are managed sustainably in all HELCOM countries, securing the productivity of agriculture and minimizing nutrient loss to the Baltic Sea environment through efficient use of nutrients and cost-effective nutrient recycling. The strategy provides a structured framework with six main objectives: establishing the Baltic Sea region as a model area for nutrient recycling, reducing environmental impacts, ensuring safe nutrient recycling, promoting knowledge exchange and awareness, creating business opportunities, and improving policy coherence. Each objective includes sub-objectives and proposed measures for HELCOM Contracting Parties to implement.

Nationally implemented, supported and tracked jointly

The HELCOM Contracting Parties, which include all Baltic Sea coastal countries and the EU, are expected to implement the strategy through national and regional initiatives. The ongoing Circular Nutrients for a Sustainable Baltic Sea Region (CiNURGi) project, funded by Interreg Baltic Sea Region, aims to support the implementation of the strategy. With partners from eight Baltic Sea coastal countries, including HELCOM, the project develops and transfers solutions to support implementation of the strategy, targeting governments, policymakers, farmers, the agricultural sector, the wastewater sector, and circular businesses.

Each objective in the strategy is linked to prioritized actions that are included in the updated BSAP. This ensures the two policy documents work in synergy, strengthening each other's impact. The implementation of the strategy will be tracked through the BSAP's follow-up mechanisms, starting in 2025. HELCOM Contracting Parties report on their progress, allowing for periodic evaluations and adjustments as needed. The HELCOM Working Group on Source to Sea Management of Nutrients and Hazardous Substances and Sustainable Agricultural Practices has key role in monitoring implementation and facilitating cooperation between stakeholders.

Towards a more resilient and sustainable future

The strategy was adopted in 2021 and is aligned with the BSAP's timeline, which runs until 2030. As the strategy is implemented, lessons learned will inform future updates. A review process will assess its effectiveness, and based on the outcomes, a new or revised strategy may be developed beyond 2030 to continue advancing nutrient recycling efforts in the Baltic Sea region.

In conclusion, the HELCOM Baltic Sea Regional Nutrient Recycling Strategy is a structured set of measures designed to tackle eutrophication and improve resource efficiency. Through enhanced nutrient recycling and coordinated efforts from governments, businesses, researchers, and farmers, it complements the BSAP and supports the Baltic Sea region's transition toward a more resilient and sustainable future.

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Sustainable use of recycled nutrients in Swedish food production – policy messages from Swedish organizations and companies

Expert article • 3807

In the project Baltic Stewardship Initiative (BSI) the need for giving constructive input to the Swedish government and national actors on new national policies for nutrient management was identified. A broad coalition of organisations, companies and experts discussed and agreed on 12 policy messages that then were presented to members of the parliament. If these policy interventions would be decided by the Swedish government, we would take big steps toward a sustainable nutrient management.

Facts on the need for a sustainable recirculation of nutrients back to food production:

- Long-term and coordinated work is needed to minimize the problem of eutrophication of the coast and sea including steering towards circular flows of Phosphorus (P) and Nitrogen (N).
- A long-term sustainable and resilient food system also requires nutrients to be managed as a resource in circular flows.
- In 2022 only approx. 9% of the N and 40% of the P in wastewater was recirculated. The future potential of the existing system, using incineration and P-extraction and N-extraction from reject water, is approx. 20% N and 90% of the P. The potential of a future source separating system is close to 100% of the nutrients in the wastewater including Potassium.
- If gradually reinvesting in a source separated system the nutrients in wastewater could over time replace up to 25% of the mineral N and 36% of the mineral P used in Swedish agriculture.

Policy messages to the Swedish Government to implement to achieve a sustainable recirculation of nutrients back to food production

1. Decide on a long-term goal of near 100% return of P and N from wastewater to food production
   - It is necessary to set a long-term goal that is not limited by today's systems and technologies.
2. Decide on a milestone target for increased return of P and N to food production
   - The government should decide that by 2030 the return of used P and N to food production must be at least 50 percent of P and 15 percent of N in the wastewater.
3. Advocate for the EU to work on the phasing out of substances hazardous to the environment and health
   - The number of chemical substances used in society is very large and for many of the substances there is still a lack of knowledge about effects, use and exposure.
4. Give the Swedish EPA the task of coordinating national upstream work and securing a central competence and support function for wastewater management and circular use of resources
   - We support this proposal from the national inquiry Sustainable sludge management
5. Investigate how a gradual transition to a source-separating wastewater system can be achieved
   - Give national agencies the mission to develop a plan for a stepwise transition to source-separating wastewater systems.
6. Develop national innovation programmes for developing high-value fertilizers from manure, wastewater, sewage sludge and food waste
   - Give the Swedish Agency for Agriculture together with other agencies this task.
7. Investigate how to support technical development of and investment in new technology for recycling nutrients from wastewater
   - Give the Swedish EPA the proposal published by the Swedish Circular Economy Delegation.
8. Regularly make new risk assessments and updating regulations on hazardous substances in wastewater, sludge and products
   - Task to Swedish Environmental Protection Agency and the Swedish Chemicals Agency as proposed in national inquiry.
9. Push EU-policy and legislation so that fertilizers are governed by the quality of the fraction and not its origin
   - Today's regulations on the provision on the market of EU fertilizer products for use in agriculture do not contain categories for, for example, sludge or wastewater.
10. Develop quota obligations that include recycled P and recycled N in mineral fertilizer
    - We support the proposal from the Swedish Parliament's Environmental Goals Committee to investigate quota obligations for sold mineral fertilizers.
11. 11. Develop a certification system for climate-smart recycled N
    - Start an investigation to propose a certification system for climate-smart recycled N. This is needed to promote technology that recovers N directly from the wastewater without risk of emitting the strong climate gas nitrous oxide.
12. Investigate additional financial incentives along the food chain to promote nutrient recirculation to agriculture
    - A national initiative is needed to identify financial incentives that increase recirculation of nutrients from wastewater.

This text is translated from the Swedish document: "*Driva på policy för en hållbar återföring av växtnäringsämnen tillbaka till livsmedelsproduktionen – gemensamma policybudskap*" https://media.wwf.se/uploads/2022/01/bsi-policybudskap-aterforing-av-vaxtnaring.pdf

Expert article • 3807

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Governmental support for nutrient recycling

Expert article • 3808

Nutrients are wasted in different parts of the food system from primary production to households, industry and waste management. Nutrients ending up in water bodies cause eutrophication and ammonia emissions cause negative climate impacts. Above all, necessary and expensive inputs for food production are wasted.

At the Baltic Sea Action Summit in Helsinki in 2010, the Finnish Government committed to intensified efforts to achieve good status of the Archipelago Sea, and the goal was to make Finland an exemplary area for nutrient recycling. Since then, measures on nutrient recycling have been implemented in Finland on a long-term basis over government terms.

Nutrient recycling is at the heart of a sustainable food system. The circular economy potential is particularly high in the more efficient utilisation of different organic side streams as a raw material for renewable energy and fertilising products. For example, in the longer term, phosphorus from mineral fertilisers needed for current plant cultivation in Finland could be replaced almost entirely by phosphorus reserves from existing organic side streams.

In the administrative branch of the Ministry of Agriculture and Forestry, the aim is to promote the use of nutrients and energy contained in manure and other agricultural biomass from a business and environmental perspective. The national Nutrient Recycling Pilot Programme has supported the recovery and production processes of organic nutrients, product development, logistics and service solutions as well as expertise and cooperation. The programme's R&D aids and investment aids together promote a circular economy in the biogas, manure treatment, nutrient recycling and carbon sequestration sectors from ideas and product development to production scale activities.

A long-prepared nutrient cycle support system for biogas plants was launched at the beginning of 2024. Operational Grants for Nutrient Cycles is operating aid for biogas plants that produce biogas and highly refined nutrient products on the market from manure or aquatic plant management waste. The aim of the nutrient recycling support is to support nutrient recycling on a commercial scale and to promote nutrient transfer, especially in areas with phosphorus surpluses. An extension of the support system is currently being prepared to cover not only biogas plants but also other nutrient recycling plants.

Nutrient recycling is promoted not only through national measures but also through the EU's common agricultural policy. The Circular economy promotion measure included in the environmental compensation in the national CAP Plan supports, among other things, the deposit of sludge and the application of organic substances to fields. This will promote the use of recycled nutrients. Environmental investments promote the use of nutrients in manure and, for example, the construction of remote manure houses. Different project supports of the CAP Plan can also be used to finance various kinds of development and innovation projects. The advisory measures provide information and AgriHubi acts as a Farmer's competence network and data bank.

Efforts have also been made in the administrative branch of the Ministry of the Environment. The Programme to promote nutrient recycling and improve the state of the Archipelago Sea, so-called Raki programme, was launched in 2012. The programme finance investments and research, development and innovation projects to promote nutrient recycling and the improvement of waters and sea. The Ahti programme of the Ministry of the Environment will continue the work.

In addition to RDI and investment subsidies, the progress of nutrient recycling has been supported by drawing up a national indicator for nutrient recycling to show the recycling potential of different biomasses in Finland.

The feasibility and effectiveness of new policy instruments to promote the use of recycled nutrients are also examined. New policy methods could include, for example, distribution obligations, use share obligations, taxation methods, effectiveness-based subsidies, development of quality systems and more efficient introduction of existing quality systems, and new combinations of several policy instruments. The aim is to promote the demand for and supply of recycled nutrients and the emergence of market-based activities, and to produce new information on policy instruments for the preparation and implementation of EU and national legislation.

In a changing global operating environment, nutrient recycling is an increasingly important part not only of environmental objectives but also of ensuring self-sufficiency in food production. The effects of climate change on food production and crises weakening the structures of the global food system challenge us to strengthen the food system. In its vision for agriculture and food in spring 2025, the EU Commission identifies nutrient recycling as one of the solutions for improving the EU's competitiveness and resilience.

New innovations, investments and products in the nutrient recycling sector are constantly emerging, but more work is still needed to mainstream the nutrient circular economy. In particular, mass logistics, with different processing methods and digital solutions in addition to physical storage, transport and distribution, is not yet sufficiently developed. The production of research-based information, collection and analysis of data are also basic prerequisites for increasing resilience. Crisis resilience can also be improved through new kinds of financing arrangements that can be used to direct private funding more efficiently to the advancement of nutrient recycling.

The next step in nutrient recycling requires a more holistic approach. We need regional and supranational solutions and new value chain examples of the profitability of nutrient recycling. In this work, the cooperation networks of Baltic Sea countries are already important and will certainly be increasingly important in the future.

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Agronomic performance of biobased fertilisers

Expert article • 3809

The focus on biomass recycling has increased markedly in recent years, fuelled by the societal goal of a more circular economy. This includes the recycling of nutrient-rich organic wastes and residues for biobased fertiliser production. Many of these new biobased fertilisers have been introduced to the European market, and a few years ago, a new EU fertiliser regulation entered into force. This aims to ensure that biobased fertilisers can enter the market with mineral fertilisers on equal terms, contributing to the circular economy of Europe. It also ensures quality standards, making biobased fertilisers reliable and safe for the user in terms of nutrient efficiency, handling and storage. In addition, it enables certification through the CE-system, certifying these biobased fertilisers contain no harmful substances or have no adverse effects on soil, environmental, or human health.

Agronomic fertiliser value

For farmers, one of the most important drivers for crop productivity is the application of fertilisers containing essential plant nutrients (nitrogen, phosphorus, potassium etc.). To ensure profitability for the farmer, efficacy of the nutrients applied for enhancing crop yield is crucial, as is the cost of fertiliser. To convince farmers of shifting from conventional mineral towards more biobased fertilisers, their fertiliser value needs to be rigorously documented.

In the EU Horizon-2020 project LEX4BIO (https://lex4bio.eu), we have tested the nitrogen fertiliser value of a range of biobased fertiliser products compared to mineral nitrogen fertiliser in field trials over two years (with maize, winter- and spring cereals) at four locations in Europe. Seven commercial pelletized solid biobased fertilisers were tested at all locations, while a number of local biobased fertiliser products (e.g. biogas digestate, food-industry by-products or compost) were tested at single sites only; in total 18 products.

The biobased fertilisers tested showed a relatively high average nitrogen fertiliser replacement value of 70% (relative to mineral fertiliser) in the crop which they were applied to. However, fertiliser value varied widely between the biobased fertilisers, with eight of them above 75%, six between 60 – 75%, while only four below 60% (11% for a compost). However, most biobased fertilisers contain some organically bound nitrogen, which is not immediately available to the first crop, but with some potential residual effect in subsequent crops. When the first and second year effects were added, the accumulated fertiliser value reached close to 100% for most of the biobased fertilisers we studied (except for compost). From a multi-annual perspective, most of them therefore showed high agronomic performance, similar to mineral fertilisers.

Risk of ammonia losses to the atmosphere

Some biobased fertilisers can be prone to nitrogen loss by ammonia volatilisation to the atmosphere, which is detrimental to the environment, but also lower their fertiliser value. We found potential ammonia loss to vary greatly across the wide range of biobased fertilisers, with highest and most rapid loss occurring from biogas digestates, while for other it was either low or occurred after a delay period. For biobased fertilisers at risk of ammonia loss, soil incorporation, as opposed to soil surface application, could be an effective mitigation strategy.

Effects on soil health

In addition to providing essential nutrients to crops, biobased fertilisers can also have positive effects on soil health. We found that biobased fertilisers generally improved soil health indicators (biological, chemical and physical) more than conventional mineral fertilisers across different European soils, but with highly variable effects between the biobased fertilisers.

Pros and cons of biobased fertilisers

Overall, we identified multiple trade-offs between the properties of the biobased fertilisers. Some were positive for soil health, but had a very low fertiliser value (e.g compost). Some were efficient nitrogen fertilisers, but did not improve soil health (e.g. potato cell water). Others had both positive effects on soil health and nitrogen efficiency, but a higher risk of ammonia loss.

We therefore cannot draw general conclusions about biobased fertilisers as a group. However, the most important determinant for farmer adoption will be price and cost of application. Many of the biobased fertilisers are not yet available in large quantities or at sufficiently low cost per amount of nutrient. Developments in the coming years will show whether supply can increase to a point where prices will fall to a level where they can compete with mineral fertilisers and in turn increase their use. Moreover, an appreciation of their other positive properties may also stimulate their use.

In any case, our results indicate the agronomic performance of most of the biobased fertilisers we studied is relatively good. This is good news for the farmers, the climate and the environment.

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Soils are resilient underappreciated helpers in the circular economy

Expert article • 3810

Looking to the future, we need to recycle more, burn less, while staying safe. The science on land-based recycling of organic wastes, indicates that soils can be amazingly resilient and helpful for us. Indeed, they are already providing services that we do not appreciate and have only just started to understand.

In the developing circular economy, we face questions on how best to manage the societal organic waste products, that inevitably contains unwanted components, such as micro-plastics, medicinal residues, heavy metals, pathogens and e.g. antibiotic resistance.

Common sense would suggest a precautionary approach, entailing advanced technical solutions, often involving incineration. However, when considering agricultural land application of animal wastes with high contents of pathogens, that has been going on for centuries, there is a cause for pause. How is it possible that humanity has survived the enormous routine application of pathogens to the land that gives us our food?

In a recent study comparing risks associated with contemporary conventional animal manure and sewage sludge we assessed risk factors mentioned above, considering the impact on the soil environment. We also considered human health impacts of antibiotic resistance in soils, and transmission of medicinal residues and heavy metals through edible plants. The main conclusion of this study was that the risk associated with agricultural use of Danish sewage sludge is comparable to that of pig slurry, once the EU limits for Zn and Cu addition to pig feed have been fully implemented.

Since 2003 we have systematically applied waste materials annually, in a long-term experiment on Copenhagen University's experimental farm. Some treatments were applied in both high and unrealistically high rates to test soil resilience to be able to assess **cocktail effects of unwanted component** in waste.

Despite exceeding legal application limits manyfold (>200 years), we have so far been unable to identify stress reactions in the soil. We have observed that addition of composted household waste and sewage sludge has resulted in several positive effects, such as increase in soil organic matter, increases in soil biota across the food web, with no negative effects on biodiversity. We found that effects on microbial antibiotic resistance appear to be short lived, and only small increases in soil heavy metal content and no increase in crop uptake of heavy metals.

While not all soils can be expected to show a similar resilience, and ability to process unwanted components, we believe that there is cause to celebrate that soils are quietly helping us. We understand that the relative strength of soils in this respect varies according to the mineralogy, the soil pH and the organic matter content, but we need to better understand the limits to their capacity as 'helpers', not least for soils that are less resilient.

Advanced technical waste incineration solutions are needed but are economically expensive and come with environmental costs that are not well understood. High temperatures cause an almost complete loss of carbon, nitrogen and sulfur, that are needed in agricultural systems, but also a decline in the quality of other nutrients, such as phosphorus. There is no current balancing of the risk avoidance with the costs mentioned above, economic costs, and human health costs related to greenhouse gas and fine particle emissions related to incineration.

Occasionally, warranted public health concerns catches the eyes of the press, as has recently happened in Denmark, where the finding of concerningly high PFAS content in free grazing cattle gave rise to a media storm. The reaction from the Danish Ministry of Environment has been to impose the strictest limits on acceptable concentrations in drinking water in the world – limits that are well below what is commonly found in rainwater, as well as very strict limits on what is acceptable in sewage sludge. When calculating the amounts of measurable PFAS in the sewage sludge applied to Danish farmland, I found that a conservative estimate yielded less than 2 kg total annually. By contrast the Danish national metabolism of PFAS has been estimated to be in the range of 20-40 tons. It my considered opinion that the regulation on sewage sludge, while expensive, will have no measurable effect on the environmental load of PFAS.

This is an example of a case where the precautionary principle has been applied, without considering the system effects, as has been a strong criticism from notabilities within sociology and law e.g. Anthony Giddens (UK) and Cass Sunstein (US). Authorities and politicians need help to balance risk versus sustainability, with as much caution as considered reasonable, considering the costs of caution. This is a complex problem, that requires input from different branches of science and should be the focus of concerted interdisciplinary research in the years to come, where the science on land ecosystem resilience will be one contributor.

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Soil health benefits from food industry residues

Expert article • 3811

The concept of the circular bioeconomy is attracting growing attention to biomass use as a basis for renewable resources. The EU Bioeconomy strategy has five goals: i) ensuring food and nutrition security, ii) managing natural resources sustainably, iii) reducing dependence on non-renewable, unsustainable resources, iv) limiting and adapting to climate change, and v) strengthening European competitiveness and creating jobs.

Food industry residues are a valuable raw material, containing ingredients like nutrients, trace elements, and organic matter. EU studies have estimated that food processing waste contributes between 12% and 41% of the total amount of food waste. On average, 5% of raw materials in the food industry end up as waste. It has high valorisation potential duo to large, homogeneous biomass amounts, but if not correctly handled, landfill deposition may cause greenhouse gas emissions and eutrophication.

In Finland, approximately 400 000 tonnes of side streams are formed in the food industry annually, corresponding approximately 8 000 tonnes of nitrogen and 800 tonnes phosphorus. It is less than 10% of the total use of mineral fertilizers annually but could be locally important.

Arable soils in the EU are subject to severe degradation. Soils are healthy when they are in good chemical, biological, and physical condition, and thus able to continuously provide their important ecosystem services, such as food and biomass production. An estimated 60–70% of EU soils are unhealthy. 12.7% of Europe is affected by moderate to high erosion, causing an estimated loss of agricultural production of €1.25 billion per year. Meanwhile, organic carbon stocks in cropland topsoil are declining, further accelerating global climate change. The use of recycled fertiliser products would contribute to reducing dependence on mineral fertilisers and improving soil health. An important goal is to reduce GHG emissions, both within value chains and through the replacement of mineral- and fossil-based fertilisers.

The EU Horizon-funded DeliSoil project (www.delisoil.eu), coordinated by the Natural Resources Institute of Finland (Luke), is contributing to the EU's Mission "A Soil Deal for Europe" by improving the sustainability of food systems and enhancing soil health. This will be achieved through the development of improved recycling and processing solutions for food industry residues.

Various processing technologies are available for non-edible food waste. These can be based on biological, chemical, or physical treatment processes, or combinations thereof. These processes can, for example, degrade organic matter, reduce water content, and bind, release or separate nutrients. The end-products could be used as organic matter -rich soil improvers, such as digestate from anaerobic digestation (AD), biochar or compost, with demonstrated improvements in soil health metrics, crop yields, and environmental sustainability.

To achieve this, guidance on actions and priorities is needed to overcome challenges and trade-offs associated with these technologies, such as potential biological or chemical risks, storage, and transport. These efforts must take into account social, legislative, economic, and environmental barriers to encourage widespread adoption.

The adoption of integrated value chains has been identified as one of the most promising pathways to accelerate the food industry's transition to a circular bioeconomy, i.e., achieving a zero-waste goal and enhancing the economic and environmental sustainability of the food production chain. Cascading use of biomass follows a downward movement in the bio-based value pyramid, progressing from higher- to lower-value biomass applications (the so-called waste hierarchy). The goal of EU fertiliser legislation (2019/1009) is to promote nutrient recycling, so it is important to determine whether additional legislative requirements are needed to minimise risks and promote the use of these products.

The DeliSoil project will perform a comprehensive evaluation of the circularity of the technological approaches. The assessment includes several key aspects: the technological feasibility of the processes, the agronomic potential of the resulting products, and the broader environmental and socioeconomic sustainability impacts of the applied technologies. By addressing these dimensions, the project aims to ensure that the proposed solutions not only function effectively but also align with the principles of the circular economy. Processing and recycling solutions for side-streams from the food processing industry have the potential to promote industrial sustainability as part of the local value chains, improve nutrient self-sufficiency in agriculture, enhance soil health and contribute to mitigating adverse environmental impacts while better controlling nutrient flows into the Baltic Sea.

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Advancing sustainable nutrient use in the BSR

Expert article • 3812

Background

Despite decades of efforts, eutrophication remains the pressing environmental challenge facing the Baltic Sea. Agricultural is a major source of excess nitrogen (N) and phosphorus (P) entering the sea, primarily due to inefficient manure and fertilizer management. Poor manure and nutrient management lead to ammonia emissions and nutrient losses through runoff and leaching, exacerbating water pollution and ecosystem degradation. These losses also represent an economic loss for farmers, as lost nutrients must be replaced with conventional synthetic fertilizers or result in lower yields.

Livestock farming in the Baltic Sea Region has become increasingly concentrated, with fewer farms managing larger herds. This intensification results in significant manure production, making effective management critical to preventing nutrient losses. Poorly managed manure contributes to environmental, economic and social challenges, degrading air and water quality while intensifying climate impacts through greenhouse gas emissions.

Sustainable nutrient use begins with recognizing manure as a resource rather than waste. Manure is rich in essential nutrients and, when properly managed, enhances soil health while replacing conventional fertilizers. Minimizing nutrient losses through improved handling, storage, and application techniques is essential for both environmental protection and economic viability. Implementing best practices in manure management can reduce environmental pressures while fostering a more efficient and resilient agricultural system.

Key strategies for sustainable nutrient management

Optimizing fertilization practices

Fertilization planning and nutrient balancing are key to ensuring that N and P applications align with crop needs, soil conditions, and expected yields. Fertilization should be planned annually at the field level to enhance nutrient-use efficiency and reduce overapplication. Given that N and P are crucial for crop production yet primary contributors to water pollution, fertilization strategies must mitigate environmental risks. Additionally, phosphorus is a finite resource, necessitating responsible management.

National or regional fertilization guidelines should be developed to balance economic optimization with environmental protection. These guidelines must be regularly updated based on field trials, new crop varieties, and changing fertilizer and crop prices. Maximum application rates should be standardized across countries to ensure consistency and prevent excessive nutrient accumulation. Soil characteristics should be determined through regular soil analysis to inform application rates and avoid nutrient surpluses.

Record-keeping is essential for monitoring fertilization planning and tracking nutrient application and should be mandatory. Digital tools like the Farm Sustainability Tool for Nutrients (FaST), part of the EU Common Agricultural Policy (CAP), can aid farmers in managing nutrients more efficiently. Adapting these tools or developing new ones for the Baltic Sea Region should be a major focus to enhance nutrient-use efficiency and regulatory compliance. Such tools can facilitate the digitalization of nutrient management, improving efficiency and compliance with environmental standards.

Farm-gate nutrient balancing is a tool that allows farmers to monitor nutrient flows, optimize inputs, enhance farm profitability, and provide insight into potential environmental risks. Annual nutrient balance calculations should assess the difference between nutrient inputs—such as feed, fertilizers, and biological fixation—and nutrient outputs, including harvested crops and manure exports. Establishing national reference values for different farm types can support accurate assessments, and integrating nutrient balance tools within FaST can provide farmers with user-friendly solutions.

By integrating fertilization planning, manure utilization, and farm-gate nutrient balancing, the Baltic Sea region can significantly reduce nutrient runoff, enhance soil fertility, and promote the long-term sustainability of agricultural production. Strengthening record-keeping systems and leveraging digital tools will further enable farmers to make data-driven decisions that optimize nutrient use while mitigating environmental risks.

Stricter minimum standards for handling and spreading manure

Clear national regulations are crucial for improving manure management and sustainability. Establishing national standards for manure quantity and nutrient content across all livestock types will ensure reliable data for effective planning. These standards should be regularly updated to reflect advances in livestock production, feeding practices, and manure processing technologies. Incorporating reference values into fertilization planning will improve accuracy in nutrient application.

Effective manure use within fertilization planning requires that applications be based on the actual N and P contents in manure, as determined by national standards. Furthermore, nutrient losses due to spreading techniques and timing must be accounted for, incentivizing the adoption of improved manure management practices. Only after optimizing manure applications should additional synthetic fertilizers be considered to meet crop nutrient demands.

A key challenge in the Baltic Sea Region is the overapplication of phosphorus (P) due to manure being spread based on nitrogen content rather than crop-specific P needs. This leads to soil P accumulation and increased runoff risks. To address this, crop-based phosphorus guidelines must be adopted, with national fertilization limits set to prevent excessive buildup. A minimum threshold of 25 kg P ha^{-1} yr^{-1} for manure-derived P, as recommended by HELCOM, should be enforced to ensure sustainable application.

To further reduce nutrient losses, manure spreading should be limited to spring and summer when crops can absorb nutrients, with autumn spreading restricted to winter crop establishment. Winter spreading on frozen or saturated soils should be prohibited, supported by investments in manure storage infrastructure to allow for better application timing.

Additionally, acceptable manure handling and spreading technologies must be defined, while outdated methods are phased out. Broadcast spreading without incorporation should be replaced with precision techniques such as trailing hoses, injection methods, and acidification, which reduce ammonia emissions and improve nutrient retention. National policies should provide financial incentives for adopting best available technologies (BAT) to make improved practices both accessible and economically viable. By enforcing stricter manure management standards, the Baltic Sea region can significantly reduce nutrient losses, enhance soil and water quality, and optimize manure as a fertilizer resource. Aligning these measures with national regulations and financial support will further drive the transition toward sustainable manure management.

Enhancing nutrient reallocation

Even with improved nutrient management, nutrient surpluses in livestock-dense areas will persist, particularly for P. Instead of redistributing livestock operations, excess nutrients should be processed into concentrated, transportable fertilizers for redistribution to nutrient-deficient regions. This approach reduces reliance on mineral fertilizers and minimizes environmental impacts of surplus nutrients.

Business models and incentives must support manure-based fertilizer production to facilitate large-scale nutrient reallocation across the Baltic Sea Region. Large-scale manure processing plants can efficiently refine manure into nutrient-dense fertilizers, but smaller-scale solutions—such as mechanical slurry separation and on-farm processing—can also help manage nutrient surpluses locally. Technologies that separate nitrogen and phosphorus into distinct products improve precision application and transport feasibility.

Assessing regional nutrient availability and crop demands is essential for effective reallocation. Data on manure and recyclable biomasses, soil nutrient levels, and crop nutrient needs should inform national and regional strategies. Investment incentives for manure processing and regional redistribution, financial support for transportation logistics, and policy mechanisms encouraging recycled fertilizer adoption will be key to success.

Manure-based fertilizers must be economically competitive with mineral fertilizers. Supporting technology development, demonstration projects, and market creation for processed manure fertilizers is crucial. Coupling nutrient recycling with renewable energy production, such as biogas generation, can further enhance economic feasibility by providing energy, improving nutrient concentration, and reducing greenhouse gas emissions.

By developing regional nutrient reallocation strategies and advancing manure processing technologies, the Baltic Sea Region can reduce nutrient losses, improve soil fertility, and promote circular nutrient use. Implementing supportive policies, investment frameworks, and technical innovations will be key to enabling this transition.

Conclusions

Achieving sustainable nutrient use in the Baltic Sea Region requires a comprehensive approach integrating mandatory fertilization planning, stricter manure management standards, and effective regional nutrient reallocation. Aligning manure application with crop needs, enforcing phosphorus limits, and adopting better technologies will minimize nutrient losses while maximizing its value as a fertilizer. Yet, surpluses in livestock-dense areas require manure processing and redistribution to balance nutrient use. Investing in manure-based fertilizers and supporting transport to crop-deficient regions will improve efficiency and reduce reliance on mineral fertilizers. A coordinated effort among policymakers, farmers, and industry is essential to achieving environmental protection, agricultural productivity, and long-term sustainability.

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Climate change, food security, agriculture and the Baltic Sea

Expert article • 3813

The role of cultivation and food production in eutrophication of the Baltic Sea has been in focus for decades. In Sweden, the debate about agriculture and the sea started in the early 1980s. In particular, events when large numbers of dead langoustines that had died of lack of oxygen were washed up on the beach in Laholm Bay on the west coast of Sweden triggered a debate about modern agriculture and the impact on the environment in general and on the sea in particular.

A long time has passed since then and it has proved difficult to achieve goals for reduced nutrient emissions. Reducing nutrient leakage from cultivation is about changing the behaviour of hundreds of thousands of farmers in the countries around the Baltic Sea. This is a completely different challenge from similar environmental work in industry or other business that is solved with engineering. For the politicians of the Baltic Sea countries, it is a difficult balancing act between, on the one hand, getting environmental measures made to live up to international commitments and, on the other hand, not creating unfair competitive conditions for their own country's farmers with increased environmental requirements or increased administrative burden.

Polluter pays principle and the price of food

The OECD's principle from the 1970s on polluter pays has not had an impact in its original form for cultivation and animal husbandry. The principle was developed for the sources of pollution of the time, with a focus on industries and other point sources. It has not proven as obvious to apply it to diffuse sources of pollution as cultivation. Over the years, economic instruments such as reverse auctions and compulsory nutrient balance calculations on farms have been discussed. Denmark and Sweden have and have had this type of policy instrument in the form of so-called fertilizer accounts (Denmark) and a tax on nitrogen in mineral fertilizers (Sweden). But on the other hand, the existing environmental legislation is a way to apply PPP because the cost of complying with it is paid by the individual farmer.

Another aspect is that measures for a more Baltic Sea friendly cultivation are also linked to the price of food. Real environmental measures cost real money and they have to come from somewhere. Since the 1970s, the share of disposable income spent on food has halved, at least in Sweden. Competition in the food market is fierce, the farmer's share of the food price is small, and this affects the pace of Baltic Sea work.

Increased circularity is important

It is important to increase the pace of making the Baltic Sea community with its food production more circular in terms of nutrients. The large cycle between urban and rural areas needs to be improved where nutrients from food are returned to agriculture without being polluted by other businesses and traffic in cities. On a smaller scale, farms in a rural area can create a local collaboration where farms with and without animals cooperate more than today. Often there is an excess of nutrients on farms with animals and a deficit on farms without animals.

Climate change increases the challenge

Increased frequency of extreme weather is bad for the Baltic Sea. This became clear after the dry summer of 2018 when leftover fertilizer nitrogen from drought-damaged plants was washed into ditches and streams and eventually into the sea. Similarly, heavy rains and floods can bring soil and pollutants from the soil to the sea. Food production is hit hard and early by extreme weather and therefore needs to be adapted to climate change. In Sweden alone, it is estimated that around EUR 5 billion needs to be invested in the water infrastructure in the agricultural landscape to cope with both drought and increased precipitation. A rough upscaling from the assessed Swedish need for measures shows that for the whole of Europe's agricultural land, the figure will be about 280 billion euros. It is starting to be of the same order of magnitude as the approximately 900 billion euros that will be invested in Europe's defense. Europe and the countries around the Baltic Sea will be forced to set tough priorities. It will be important that money is invested in measures that, as far as possible, provide cleaner oceans and climate adaptation at the same time. This is also a question of food security in the Baltic Sea region.

Lessons learned

There is now a lot of knowledge about concrete environmental measures to be taken in agriculture, but measures need to be taken on a much larger scale. It is a political issue to invest enough money in measures, because the necessary volume of environmental measures cannot be paid for on farms on their own with the price of food. The development going forward will be a continued race between the pace of environmental action, climate change and the continued population growth around the Baltic Sea.

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Recovered nutrients – Farmers' perspective

Expert article • 3814

Nutrient management is at the heart of sustainable agriculture, yet imbalances in their availability pose challenges for farmers across regions. While some areas struggle with excess nutrient accumulation, others face shortages that limit crop production. At the same time, industries generate nutrient-rich by-products that often go to waste. Could recovered nutrients be the answer to these challenges? As interest in alternative fertilizers grows, farmers consider three key factors when adopting them: product quality and safety, ease of handling and application, and clear nutrient composition.

As a result of geographical, economic and political developments, the agricultural sector, especially livestock farming, has concentrated in certain regions, creating excessive nutrient accumulation in "hot spots." Even within the Baltic Sea region, the density of agricultural animals varies significantly across different areas, and consequently – the availability of nutrients for the crop production sector also differs. Similarly, with the development of food processing and other industries, large volumes of side products are created, in which nutrients necessary for plant growth are concentrated. Challenges are created by sludge from wastewater treatment processes and ashes from various combustion processes. These materials are geographically concentrated in or near densely populated areas. Managing by-products together with the rest of the waste stream, by disposing them in landfills or incinerating them, is not a good resource management process, and in many cases is economically disadvantageous.

At the same time, the agricultural sector is experiencing increasing challenges – limited availability of organic fertilizers and rising mineral fertilizer prices, which leads to searching for alternative fertilizer solutions. Nutrient supply is a special task for organic farmers and any farmer in regions where soils are poorer, livestock density is lower, and mineral fertilizer availability is limited. Due to all these circumstances, farmers' interest in fertilizers based on recovered nutrients is continuously growing. However, several conditions remain very important for farmers to purchase and use these fertilizers on their farms.

First, the **quality of the fertilizer material**. Regardless of the raw material from which the fertilizer is derived, it must fully meet safety criteria. The main ones, clearly defined in most European countries, are the concentration of heavy metals and contamination with pathogens. There are limit values at which the material is not allowed to be used in agriculture. Two other groups of contaminants are microplastics, as well as medication and antibiotic residues. These are things that farmers do not want to see in the material.

The second important aspect for using recovered nutrient fertilizer - **the material must be easy to load, transport, and spread**. Farmers have specific types of equipment that allow for uniform field distribution of two specific types of materials: liquid – with a dry matter content of up to 10%, or dry, free-flowing – with a dry matter content of ~50% (min 30%). For example, if compost is being made from semi-liquid mass, sufficient filler (garden and park waste; ash; etc.) needs to be added to obtain a free-flowing product. Similarly, pure wood ash cannot be used as fertilizer in agriculture. It is granulated together with other material combinations. Also, for the biochar, it is advisable to add bran or other materials to improve physical properties.

As a third factor, the **definition of recovered nutrient materials in a way that is understandable and comprehensive to farmers** should be mentioned. Understanding of the product and what's inside is important. Farmers, when preparing fertilization plans for their fields, balance nutrients by combining different types of fertilizers. However, if the fertilizer is given a nitrogen, phosphorus, or potassium content, these substances must be indicated in such a chemical form that the farmer can directly include the nutrients in their calculation formulas without any additional conversions being necessary. For example, there is a difference whether calculations for fertilizer balancing are done with phosphorus or phosphorus oxide. It is also important for farmers to know the microelements content of fertilizers, as each element plays an important role in the overall system operation, and its deficiency or overdose can cause undesirable consequences. For example, if the recovered fertilizer contains copper (Cu) or zinc (Zn) residues, it is important to know their quantity to later avoid unnecessary concentration of specific elements when using foliar fertilizer or some other complex fertilizer.

Sustainability goals, which most companies try to implement in their operations, lead to searching for solutions. For farmers, the availability of quality fertilizer is important, while for companies in other industries and society – finding solutions for sustainable processing and use of side streams is challenge. Cooperation between players from various involved sectors leads to systemic solutions that allow closing the nutrient cycle and keeping nutrients in the system. This enables sustainable resource management and prevents risks to nature, the environment, and people.

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EVA SALOMON

How can improved N and P balances meet farmers' needs?

Expert article • 3815

Fertilizer use in Swedish agriculture was limited until the 1950s, with farmers relying on integrated crop and livestock systems that maintained a biological balance. Crop rotation with legumes provided nitrogen, but low input of purchased fertilizers restricted production. With cheap fossil energy, fertilizer application increased until the late 1970s, leading to specialization and breaking the nutrient cycle between livestock and crop production. Animal-intensive farms had excess manure, while the availability of cheap fertilizers reduced farmers' incentives to utilize manure efficiently. The result was surplus nitrogen and phosphorus application, contributing to eutrophication in water.

At the start of the 21st century, Sweden introduced environmental quality objectives requiring agriculture to reduce nitrogen and phosphorus losses. Financial support enabled action, and farmers actively engaged in achieving these goals. Representatives of farmers, advisors and authorities joined forces to launch a campaign of introducing free advisory services emphasizing individual farm visits and nutrient balance calculations. More than 18,000 nutrient balances were conducted over 15 years. Evaluations showed that combining balance calculations with advisory services improved nutrient management, leading to declining nitrogen and phosphorus losses.

The free advisory service attracted many farmers, offering a whole-farm perspective on nutrient handling. Farmers with both crop and livestock production found this particularly valuable for achieving profitable yields. Most farmers reported savings in costs and workload as an effect of improved nutrient management. Future farmers will still have incentives to optimize nutrient use while working toward sustainability. Those already convinced will continue seeking advice, while others, previously without access to advisory services, benefit from the free support as a starting point.

Nutrient imbalances can create conflicts between short-term animal health and long-term soil fertility. Knowing the nutrient content of manure is crucial for planning crop fertilization on a farm with livestock production. Accurate calculations, based on farm-specific data, help farmers optimize nutrient use. Nutrient balance calculations typically rely on data from purchased and sold products at the farm-gate. Farmers with livestock production should benefit from account for nutrients in feed, manure, and livestock production as nutrient amounts circulating within farm are substantial. With advisory support and access to nutrient values for currently used feedstuffs the farmer receives an optimized feeding plan and a calculation of the amount of plant nutrients in manure coming out of the stable. That would prevent excess nitrogen and phosphorus in animal diets, which would otherwise accumulate in manure and increase environmental risks.

Manure management is critical for maximizing its fertilizer value. Proper storage prevents phosphorus losses, while nitrogen losses, primarily through ammonia volatilization, can be minimized with best management practices. Crop field trials confirm that phosphorus in manure is as effective to crops as synthetic fertilizers, meaning livestock farmers often have sufficient phosphorus without additional purchases. However, nitrogen is the key factor for yield, and farmers often overapply manure and fertilizers, increasing nitrogen losses. Farmers receiving advise concerning nitrogen balance calculations, ammonia loss assessments, and best practices for manure application improve the nitrogen use efficiency. New knowledge about best manure management is transferred to the farmer through free courses and study visits. Individual advisory services provide tailored guidance.

The farmer knows that effective manure management offers multiple benefits: improved animal housing climate, cleaner livestock, reduced odor, and lower reliance on synthetic fertilizers. Farmers recognize its importance for sustainable food production and environmental protection. However, motivations vary—some seek cost savings, others aim to prevent stricter regulations, meet consumer expectations, or ensure their farm's long-term viability. Addressing these diverse incentives is key to engaging farmers in achieving environmental goals.

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Closing the nutrient loop: Stakeholder insights from CiNURGi

Expert article • 3816

The Baltic Sea, one of the most polluted seas in the world, faces significant challenges from nutrient runoff, leading to eutrophication and biodiversity loss. Recognizing this critical issue, the EU Interreg Baltic Sea Region (BSR) core project CiNURGi—Circular Solutions for Nutrient Recovery—aims to foster nutrient recycling, enhance agricultural sustainability, and advance a circular economy across the region. Central to CiNURGi's success is stakeholder engagement, which ensures sustainable and impactful transnational collaboration.

The stakeholder-centric vision

CiNURGi integrates perspectives from business owners, wastewater treatment operators, policymakers, research institutes, and private industries across the Baltic Sea Region. By collaborating with such a diverse stakeholder base, the project ensures its efforts are scientifically robust, practical, inclusive, and adaptable. This multifaceted approach enables CiNURGi to address critical environmental challenges while fostering regional cooperation. By focusing on circular nutrient systems, the project facilitates the recovery of valuable resources such as phosphorus and nitrogen from wastewater sludge and promotes practices like biochar production to reduce dependency on synthetic fertilizers. Moreover, cross-sector collaboration bridges agriculture, wastewater management, and policy, creating synergies that amplify the project's regional and long-term impact.

Circular economy practices: The example of Sweden

The Testbed Ellinge project in Sweden exemplifies the transformative potential of integrated pilot projects and stakeholder engagement in advancing the circular economy. Led by **VA SYD** at the Ellinge Municipal Wastewater Treatment Plant in Eslöv, the facility demonstrates the cutting-edge capabilities of sludge pyrolysis technology. The testbed operates with a multidisciplinary team comprising universities, research institutes, and companies, reflecting a robust collaboration across sectors. Part-financed by the Swedish Innovation Agency, Vinnova, the project also includes four additional municipal water and wastewater utilities as key partners, enhancing its reach and impact.

By converting wastewater sludge into biochar, the testbed achieves several significant outcomes. Phosphorus is efficiently extracted for reuse, reducing dependence on synthetic fertilizers while promoting sustainable agricultural practices. Additionally, the pyrolysis process sequesters carbon, contributing to climate change mitigation. The resulting biochar acts as a highly effective soil improver, enhancing long-term soil fertility and resilience in agricultural systems.

Beyond its technological advancements, Testbed Ellinge serves as a model of stakeholder engagement. The facility hosts workshops and site visits, enabling business owners, municipal planners, researchers, and other stakeholders to observe its processes firsthand. This open and inclusive approach fosters transparency, trust, and active knowledge sharing, inspiring similar initiatives across municipalities and regions. By combining practical demonstrations with active collaboration, Testbed Ellinge provides a compelling example of how circular economy solutions can be effectively applied in real-world settings.

Policy alignment and advocacy

Policy alignment is a cornerstone of CiNURGi's stakeholder engagement strategy, ensuring its initiatives resonate regionally and at the EU level. By aligning with the EU Green Deal, CiNURGi contributes to reducing reliance on fossil-based fertilizers and mitigating nutrient runoff into the Baltic Sea. The project also actively supports the Baltic Sea Region Nutrient Recycling Strategy by advancing the objectives outlined in this HELCOM Action Plan. Through its workshops and dialogues and collaboration with and the EU Strategy for the BSR Policy Area Nutri, CiNURGi advocates for practical policy measures, such as introducing quotas for recycled nutrients in fertilizers and providing financial support for pilot plants that develop innovative recovery technologies. Furthermore, the project emphasizes the need for tax incentives to make bio-based fertilizers economically competitive. These initiatives collectively aim to drive systemic change, ensuring that nutrient recycling solutions are scalable, cost-effective, and widely adopted across the Baltic Sea Region.

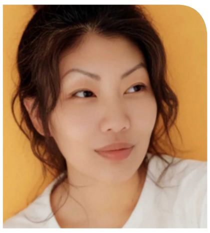
Future outlook: Scaling impact

Looking ahead, CiNURGi aims to amplify its impact by scaling its initiatives across the Baltic Sea Region. Building on the success of pilot projects like Testbed Ellinge, the project plans to replicate its solutions in other countries, demonstrating how circular economy practices can adapt to diverse environmental and economic contexts. Equally important is policy integration, where CiNURGi's findings will inform regional strategies, influence funding priorities, and shape regulatory frameworks that support nutrient recycling and sustainable agricultural practices.

In addition to scaling solutions, a potential further outreach and impact of CiNURGi is to broaden stakeholder participation by actively involving underrepresented groups. Smallholder farmers, for example, are directly impacted by fertilizer policies and stand to benefit significantly from circular practices. Community organizations also play a critical role in driving local-level implementation and advocacy. By engaging these groups, CiNURGi can continue to enhances its social equity dimension while fostering grassroots support for circular economy initiatives. As the Baltic Sea Region transitions toward sustainability, CiNURGi's stakeholder-driven model serves as a blueprint for inclusive and transformative change.

Conclusion

CiNURGi exemplifies how circular economy principles can thrive through cooperation, innovation, and shared responsibility. By fostering collaboration across sectors and nations, the project not only addresses nutrient pollution but also builds a resilient and sustainable future for the Baltic Sea Region. With its stakeholder-centric approach, CiNURGi paves the way for global efforts to close the nutrient loop and advance sustainable agricultural practices.



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The situation of nutrient recycling in Denmark

Expert article • 3817

Denmark stands out in the Baltic Sea Region for its high agricultural intensity, but also for its commitment to environmental responsibility. With the highest livestock density in the region and extensive farmland use, Denmark faces significant challenges in nutrient management. However, the country has taken a proactive approach, integrating nutrient recycling into its environmental and agricultural policies. By optimizing the use of nitrogen (N) and phosphorus (P), Denmark aims to balance food production with sustainability, setting an example for other nations striving for circular nutrient management.

Denmark has the highest livestock density in the Baltic Sea Region (BSR), with 1.59 Livestock Units per hectare of agricultural area. Around 61% of Denmark's land is cultivated, over twice the EU average. Additionally, Denmark is densely populated with 141 people per square km, second only to Germany in the region. This results in a higher turnover of nitrogen (N) and phosphorus (P) compared to other BSR countries. However, Denmark prioritizes environmental cleanliness for health and business reasons. Nutrient recycling, essential for reducing pollution and greenhouse gas emissions, is central to Denmark's water action plans, which set concrete targets for reducing nitrogen and phosphorus losses.

Nutrient recycling facts

Looking at the facts, the Danish demand for nutrients for crop production is about 380 thousand ton, kt N and 53 kt P. To cover this, 216 kt N and 48 kt P are provided with livestock manures, 4 kt N and 1 kt P are recycled from wastewater, while 22 kt N and 10 kt P are recycled from other wastes, including food waste and industry wastes. Furthermore, 238 kt N and 11 kt P are provided with mineral fertilisers. Consequently, there is a surplus of 100 kt N and 17 kt P, which is lost to the environment. In addition, about 22 kt N and 5 kt P in wastewater is not recycled, but N mainly converted to nitrogen gas (N2), and P mainly precipitated as an inert compound. With other words, farming is responsible for about 90% of the total turnover of N and 78% of the P.

Since the above-mentioned surplus comprises a loss of 49 kt N and 9 kt P from manure field spreading, specifically caused by a regulated inefficiency in recycling of nutrients in livestock manures, the farming sector would need to have a dominant role in efforts to increase nutrient recycling. Today, almost one fourth of the N in livestock manures brought to the fields are not to be accounted for, neither any of the N losses from stables and stores, and P regulations introduced in 2016 have not proven to be effective for moving a surplus of P from the western part of Denmark to the eastern part with more intensive crop production and P deficit. Next to farming, there is a potential for higher nutrient recycling in the wastewater sector. The process of wastewater treatment was established decades ago and compromises several current policy areas. For example, it renders P inert, which is a depleting resource, and releases N as N2 gas, resulting in significant emissions of nitrous oxide. Overall, the current nutrient self-sufficiency is 51% for N and 98% for P. However, the self-sufficiency for P is in reality only around 50% due to the current lack of incentives for regional redistribution.

Denmark's nutrient recycling is good internationally, and the advanced and detailed way farms do nutrient accounting is probably a good example for any other country. But there is anyway considerable room for improving nutrient recycling.

Nutrients coherent policies

Given the role of nutrients in Danish policies it is characteristic that political negotiations about the way to reach Denmark's goals for 70% greenhouse gas emission reductions in 2030, compared to 1990, led to an "Agreement on a green Denmark" in 2024, that despite from being unique in a global perspective by imposing a climate tax on farming, is seen as much as a nutrient accord, since it will greatly influence Denmark's self-sufficiency with plant nutrients. The deal means that the N losses will be reduced with 13,780 ton and about 15% of the cultivated areas in the country converted to un-fertilised forests and other nature areas by 2030. The agreement means that the self-sufficiency could reach 55% for N and 109% for P.

Higher recycling and 100% self-sufficiency are feasible political choices

Achieving the EU's overarching policy goal of a circular economy for nutrients would offer significant benefits for our environment, climate, health, soils, biodiversity, nature, critical raw materials, and overall welfare. We are close to this milestone for P, with regional re-distribution incentives being the key to reaching it. For N, three principal focus areas provide a feasible path forward.

Firstly, it is viable to shift crop demands from crop economic optimal N dosing to society optimal N dosing, which would entail approximately 15% lower N doses, thereby reducing N demand by 57 kt. This approach was implemented in Denmark from 1999 to 2015 and largely did not affect crop productivity statistics.

Secondly, the unaccounted N share in livestock manures can be progressively reduced to half, utilizing existing manure handling technologies on a broader scale.

Thirdly, there is substantial potential in modifying crop rotations to include more nitrogen-fixing crops, adopting regenerative farming practices, and incorporating microorganisms that mimic the ability of nitrogen-fixing plants to absorb nitrogen directly from the atmosphere and mobilise P in soils.

Besides that, it is essential, but also fair and reasonable, that wastewater treatment plants and waste collection companies meet the same nutrient recycling standards as the farming sector.

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Nutrient recycling in the Baltic Sea Region

Expert article • 3818

The predominant method of nutrient recycling in the Baltic Sea Region (BSR) involves the use of animal by-products (livestock manure), digestate and sewage sludge on arable land, typically following sanitation or other moderate treatment processes, such as composting. Some BSR countries have certification schemes, such as the Revaq scheme (https://www.ri.se/en/expertise-areas/services/certification-of-wastewater-treatment-plants-revaq) in Sweden. Germany is an exception in that it requires phosphorus (P) to be technically recycled if wastewater treatment plants exceed a population equivalent of 100,000 from 2029 and 50,000 from 2032. The preferred recycling route in Germany will be mono-incineration of sewage sludge and recovery of P from the ash, in compliance with the German Sewage Sludge Ordinance (AbfKlärV, https://www.gesetze-im-internet.de/abfklrv_2017/), and a minimum P recovery rate of 80%.

Germany is the only BSR country pursuing technical nutrient recycling, but the Nordic countries have advanced technical recycling companies and promising recycling initiatives.

EasyMining AB (www.easymining.com), part of the **Ragn-Sells Group in Sweden**, specialises in nutrient and material recycling. The company has developed several innovative processes for recovering valuable resources: The Ash2Salt process for salt recovery from municipal solid waste incineration fly ash with a capacity of 130,000 t/a is already in operation in Upplands-Bro, near Stockholm. Two Ash2Phos plants with a combined capacity of 60,000 t/a of sewage sludge ash (SSA) have got operating permits and construction will start in 2025 in Schkopau (Germany) and 2026 in Helsingborg (Sweden).

The Ash2Phos process is characterised by an acid attack of the SSA, followed by a series of precipitation steps to separate the different material streams. Phosphate is recovered in the form of calcium phosphate, iron and aluminium are returned to the wastewater treatment plant as coagulants, the silicate residue is suitable for cement replacement and the metals are potentially delivered to smelters for copper and zinc recovery.

The most important characteristic of the Ash2Phos products is their high purity - the material streams are separated to such an extent that the recycled product contains no relevant impurities or pollutants. The return of materials to their original function also reduces the environmental footprint - each stream replaces a primary raw material stream with sometimes relevant carbon emissions. Furthermore, calcium phosphates from the Ash2Phos process have been recommended for use in certified organic farming by the EGTOP expert group, and the European Commission has already proposed a corresponding amendment to Regulation (EU) 848/2018 and the implementing Regulation (EU) 1165/2021. Aqua2N is characterised by the removal of ammonia from the liquid phase and the reaction of the gas with sulphuric, phosphoric or nitric acid to form an ammonium sulphate, phosphate or nitrate solution that can be crystallised into a solid fertilising product.

LKAB, the **Swedish** state-owned **mining and minerals group**, has launched a highly relevant mining and recycling initiative (https://lkab.com/en/what-we-do/our-transformation/critical-minerals/). At its Per Geijer mine north of Kiruna, where apatite is the main valuable mineral apart from iron ore, phosphate and rare earth metals - the latter needed for wind turbines, electric cars and mobile phones - can be extracted as by-products. For many years, apatite was separated from iron ore and stored in mine tailings because it was not profitable to produce phosphate fertilisers. Recently, a new technology has been developed that makes phosphate processing economically viable. The initiative is supported by recent geopolitical developments and the European Commission's Critical Raw Materials Act, which aims to increase supply chain resilience and reduce dependence on supplies from less reliable countries. Some European fertiliser manufacturers and distributors rely on supplies of phosphate rock with negligible cadmium concentrations, partly due to the use of a processing by-product such as phosphogypsum in construction applications, and partly due to low cadmium limits in fertilisers in Nordic countries. Currently, the only low-cadmium source in the EU is the Siilinjärvi phosphate rock mine in eastern Finland. Beyond the EU's borders, Russia has similar low-cadmium magmatic phosphates, but the EU should avoid co-financing the war in Ukraine by importing phosphate rock and fertilisers from Russia. The Per Geijer mine could supply seven times Sweden's P fertiliser needs and become a significant source of clean phosphate in the EU.

LKAB is gradually implementing these plans. The apatite will be concentrated at the mine sites and transported to a new industrial park in Luleå, where the phosphorus and rare earth elements will be processed. LKAB's resources and reserves are estimated at four billion tonnes of iron ore, about twice the amount mined since 1980. "LKAB has applied for the iron ore mine in Gällivare, the planned industrial park in Luleå and the Per Geijer iron ore deposit in Kiruna, which is rich in rare earth elements and phosphorus, to be designated as strategic projects under the EU's Critical Raw Materials Act" (https://lkab.com/en/press/lkab-constructs-facility-for-critical-minerals-the-first-of-its-kind-in-europe/, accessed 24/03/2025).

HSY Helsinki's RAVITA Process (https://www.hsy.fi/en/ravita/process/) is a cutting-edge technique for the direct recovery of phosphorus and nitrogen from wastewater at the final stage of treatment. For P recovery, phosphorus is removed from treated wastewater through a chemical precipitation process. The resulting precipitate is then dissolved using phosphoric acid. Following dissolution, the phosphorus and the precipitating chemical are separated. The precipitating chemical is then recycled back into the post-precipitation process. A portion of the recovered phosphoric acid is reused in the process, while the excess becomes a product for the fertiliser industry and potential other industrial applications. Nitrogen recovery is applied to the reject water (condensate) from sludge drying with high ammoniacal nitrogen content. This nitrogen is recovered using a stripping process that utilises the recovered phosphoric acid. The end product is ammonium phosphate, which can be used as a fertiliser straight away. The process offers a sustainable way to purify wastewater while recovering essential nutrients for agricultural and industrial use.

The RAVITA DEMO pilot plant, situated at the Viikinmäki wastewater treatment plant, is engineered to evaluate the phosphorus recovery process on a reduced scale. It serves a population equivalent of 1,000 and is divided into three key areas:

A. Chemical sludge production with three steps: 1) Precipitation – phosphorus is removed from wastewater. 2) Disc filtration – removes nearly 95% of phosphorus in the first stage. 3) Sludge drying – preparing sludge for further processing.

At full-scale operation, two precipitation and separation stages will be needed to ensure very low phosphorus levels in the effluent. The resulting chemical sludge has a low heavy metal content, making it cleaner than sludge from traditional co-precipitation.

B. Sludge dissolution and phosphoric acid treatment: the process of breaking down sludge and refining phosphoric acid is being optimised. The objective is to transform the recovered phosphorus into a marketable product for industrial application.

The RAVITA DEMO plant is instrumental in refining this technology before its large-scale implementation in wastewater treatment plants.

The examples of cutting-edge technologies for nutrient recycling in the Baltic Sea Region have been selected by the author for their sustained development and backing by powerful institutions. The selection is based on the author's experience and is non-exhaustive. The author is aware of ongoing research projects that will complement the list with alternative approaches and some of these are partly presented in the same BRE Review issue.

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The Swedish nutrient platform

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The concept of a circular economy is gaining traction in many fields, although in certain sectors, the transition is complex and somewhat slow. One of the more complex sectors is nutrient reuse and recovery from wastewater. There are many challenges that must be overcome before this transition is successful. These include, but aren't limited to, policy and regulations, public acceptance and economic factors. The complexity of the issue is immense and depending on factors such as wastewater treatment methods, catchment area, geographical context and soil health. The prices of energy, chemicals and fertilizers, regionally and world-wide, also play an important role. There is no "one technology fits all" solution.

The Swedish Nutrient Platform plays a crucial role in the Swedish transition by engaging the entire value chain from wastewater to agriculture in discussions, projects, and conferences. This collaborative approach helps to bridge challenges and to develop innovative solutions for utilizing nutrients from wastewater in agriculture. The issue at hand is not isolated. Both the agricultural industry and the wastewater sector face numerous challenges. Circular nutrient management could help address challenges in both sectors. However, there is always a risk of new issues arising as new value chains are created. Concern about micropollutants and PFAS being top of the discussions today.

Achieving sustainable nutrient utilization from wastewater as introduced earlier involves navigating acceptance, technology, regulation, economics, infrastructure, and the need for new paradigms. Currently, agriculture is heavily dependent on mineral fertilizers produced mainly from fossil fuels and virgin materials. Nutrients in these fertilizers eventually end up in our food system and, after digestion, in our wastewater. By finding ways to recirculate these nutrients back into food production, we can reduce dependency on fossil fuels and virgin materials, helping agriculture to achieve climate neutrality. This approach also reduces the amount of reactive nutrients in the environment which mitigates eutrophication. Circular nutrients from wastewater could play an important role in future agriculture practices, but they cannot fully replace all the fertilizers currently used. If the fertilizing system continued to become more effective, with fewer losses and reduced needs, circular nutrients from wastewater, could be a significant source of nutrients.

While nutrient recovery from wastewater might seem like a minor issue, it involves many different stakeholders including food producers, water suppliers, industry, and urban wastewater managers. The stakeholders did not have a natural arena to meet and discuss these issues, which motivated the Swedish nutrient platform to take form. It also in ways includes the whole of society as consumers of food and the acceptance from them is crucial for nutrient recovery solutions to be successful. Nutrients from wastewater has potential to contribute to a more resilient food system, but the key question is how to create a product with market value from what is typically considered a waste product. The forerunners in nutrient recycling have taught us the importance of finding sustainable value chains and building long-term relationships with buyers of the product, as prices can be decreased —not because of product quality but because the product is produced continuously as a function of the 24-7 operation of wastewater treatment plants and potential customers know that storage space will soon enough be critical. Wastewater treatment plants typically aim to separate nutrients from incoming wastewater in order to prevent their release into receiving waters. This is core business for any urban wastewater manager. However, in some cases, the mission also includes making these nutrients available for reuse as fertilizers. In Germany, for example, the legislation requires the recovery of phosphorus from wastewater treatment sludge. In the revised 'urban wastewater treatment directive, phosphorus recovery will be mandatory across the European Union, but targets are yet to be decided. The revised directive also states that targets for nitrogen recovery are to be evaluated for future inclusion.

The Swedish Nutrient Platform, led by RISE Research institutes of Sweden and IVL Swedish Environmental Research Institute, focuses on raising awareness and bringing together a diverse range of stakeholders to work towards sustainable fertilizer production and nutrient reuse from wastewater. The platform serves as a knowledge hub, providing easily accessible information and facilitating collaboration among stakeholders to address issues and initiate new projects. The platform and its members are making plans for a circular future and finding ways to get there.

If you're interested in the platform, please contact the project managers Elin Kusoffsky (elin.kusoffsky@ri.se) and Lisa Gren (lisa.gren@ivl.se).

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LEX4BIO Horizon project and its results

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Agriculture is the main source of external nutrients to the Baltic Sea, enhancing eutrophication, which is evident as algal blooms. The main nutrients causing eutrophication are nitrogen and phosphorus, which at the same time are essential for sustaining agricultural productivity. Therefore, these nutrients are applied via fertilization, but excessive application increases the risk of losses through volatilization or leaching.

Prior to World War II, fertilization was mainly conducted by using various organic nutrient-rich side streams, such as manures. However, population growth accelerated significantly from the 1950s onwards, putting pressure on agriculture to produce more food for the growing population. One of the main causes of increased productivity during the Green Revolution in 1960s was the increased use of mineral fertilizers. Since then, fertilization has commonly been conducted with mineral fertilizers, peaking in the 1980s. In the 1990s, fertilization recommendations were lowered to better match crop requirements, improving the utilization of phosphorus fertilizers and reducing nutrient losses to surface waters.

All this time, a vast amount of nutrient-rich side streams was produced but considered waste and not an option for replacing mineral fertilizers. Recently, however, there has been growing interest in turning nutrient-rich side streams into bio-based fertilizers (BBFs) to replace mineral fertilizers, decrease dependency on imported fertilizers, and reduce environmental problems.

In the Horizon 2020 -project LEX4BIO (https://lex4bio.eu/), we evaluated the potential of BBFs to replace conventional mineral nitrogen and phosphorus fertilizers in Europe. LEX4BIO focused on the most promising technologies for BBF production, their fertilization efficiency, and potential impacts on food and feed security and human health. The most important impact of the project was to provide technologies for developing safe BBFs, along with a policy framework for the EU's transition to maximizing fertilizer self-sufficiency by using BBFs, while minimizing potential risks.

Screening of both available BBFs and emerging processing technologies, a wide selection of BBFs was tested, considering the new fertilizing products regulation (EU 2019/1009) that allows free movement of CE-labelled fertilizers across the EU. A total of about 40 nitrogen and 40 phosphorus-containing BBFs were selected for testing from laboratory to field scale. From a farmers' point of view, the fertilization efficiency of BBFs compared to mineral fertilizers is a pivotal issue. Thus, both greenhouse and field trials were conducted in different climatic and soil conditions in Finland, Denmark, Germany, Austria, Hungary, France, and Spain to ensure comparability among different growing conditions. The results clearly showed that both nitrogen and phosphorus-containing BBFs can efficiently replace mineral fertilizers and thus reduce dependency on them.

The main concern for consumers is whether BBFs affect food safety. Potential heavy metals and organic contaminants, including pharmaceuticals, pesticides, and persistent organic pollutants (POPs; including PCBs, PAHs, PCDDFs and PFASs) are a major concern. A large screening of these contaminants was conducted for both the BBFs and the harvested crops. Heavy metal concentrations in the BBFs were below the limits set for the fertilizers and, in some cases, significantly lower than those in mineral phosphorus fertilizers, such as cadmium. Organic contaminants were also below the strictest limits set in the EU member states. From an environmental perspective, BBFs caused lower phosphorus losses than mineral fertilizers. One emerging concern relates to antibiotic resistance genes, which could potentially reduce the efficiency of currently used antibiotics. Although some BBFs contained pharmaceutical residues, these BBFs did not pose a risk of disseminating antibiotic resistance in the soil.

At the European level, nutrient-rich side streams could almost fulfill the crop requirement for phosphorus fertilization due to decades of overfertilization. However, this requires processing these side streams into more concentrated BBFs to reduce transportation costs from nutrient-surplus to nutrient-deficient regions. Unlike phosphorus, nitrogen fertilization is needed annually for optimal yields due to its leaching losses and the risk of ammonia volatilization. In the Baltic Sea region, data on the locations and amounts of these side streams is needed to evaluate their potential to replace mineral fertilizers.

All reports and publications of LEX4BIO can be found at the following link https://cordis.europa.eu/project/id/818309.

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Bioeconomy exchange between the EU and Africa

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Successful transfer of technologies between the EU and Africa is possible and it benefits all, as it supports the environment by converting agricultural waste into valuable resources and promoting sustainable growth in the bioeconomy.

New technologies often take a long journey from idea to market, especially when transferring technology from Europe to Africa, which may take many years.

However, in Bio4Africa (www.bio4africa.eu), a four-year EU Horizon Research and Innovation Action project, we have adapted two young bioeconomy technologies to local conditions and transferred them to four African countries.

These two technologies also have implications for carbon and nutrient recycling – especially on the African continent – and are examples of a new way of thinking about bioeconomy and indeed a way to ensure optimal use of biogenic carbon in the agricultural ecosystem.

Agricultural waste biomass pyrolysis

In Europe, pyrolysis of waste biomasses has recently been introduced to produce biochar as carbon storage in agricultural soils, helping to counteract Green House Gas emissions. Many millions of euros have been invested in developing these technologies for large-scale and high-tech applications – and often coupled directly with biogas production and the circular nutrient handling in the bioeconomy.

In the project Bio4Africa, we have introduced a Brazilian pyrolysis kiln technology and demonstrated the usefulness of this technology on waste agricultural biomasses. It is cheap (costs around 5000 € and is easy to build for locals with a construction manual) and yet much better than traditional pyrolysis technology.

This pyrolysis process, using agricultural waste such as mango stones, coconut shells, corn cobs, cashew nut shells etc., has several purposes:

1. to avoid deforestation and make agricultural waste biochar available to replace woody biochar
2. to make value out of large piles of biomass waste.

The biochar can be used – depending on the local needs and value optimization –

- either as a soil amendment to increase the productivity of acidic, leached soils (tested in combination with traditional fertilizers for maize, okra and tomatoes) or
- to produce briquettes of waste biochar for local cooking (either directly or transformed into briquettes).
- to use the activated biochar for purifying drinking water in villages

It has even shown promising positive effects on the production of biogas in the lab, but this must be verified.

Figure 1 Newly constructed Brazilian kiln with four chambers and common chimney and resulting corn cob biochar in Loagri, Ghana

Green protein refinement

Another promising concept and technology successfully implemented in Uganda and Ghana is the collection and processing of green leaves (grasses, legumes and combinations of these) through a robust and simplified 'slow juicer'.

The technology used in the projects has been brought in from elsewhere, but it is not very complex. Grassa BV, a company based in the Netherlands, has marketed this product to European dairy farmers, and it is now being tested and implemented in Uganda and Ghana.

The idea is to produce multiple value streams from grass and/or legume leaves:

1. The press cake contains crushed leaf cells with highly digestible proteins as valuable fodder for ruminants – either fresh or ensiled for later use. Even if much protein has been separated into the juice, the press cake still has a high fodder value. The manure nutrients (especially P and K) can be recirculated into the grass/legume fields.
2. Lactic acid bacteria are added to the juice to make coagulated proteins and a whey containing most sugars and minerals.
3. The coagulated proteins are separated and dried by sun or air and can be used in fodder mixtures for poultry, pigs, rabbits and fish, thus making local green proteins valuable for more livestock species.
4. The brown juice can be further refined (we are testing several interesting high-value ingredients in Bio4Africa), the juice can be fed to pigs or into a biogas digester or can be used directly as a fertilizer (containing P and K) in the fields, where the green plants were harvested.

The first African installation of a protein refining plant was installed in Uganda in 2023, only a few years after similar plants were commercially launched in Europe. Green protein refinement has great potential to improve local nitrogen recycling system and create additional value streams for villages and cooperatives.

Figure 2 Protein refinery in Fort Portal, Uganda. Left washing of leaves, right tanks for protein coagulation and whey

Innovation transfer

These two examples demonstrate that African countries can innovate, adapt and apply technologies and concepts as intermediates between the more efficient, costly and advanced pyrolysis and biorefinery plants of Northern Europe and the needs of local communities dominated by smallholder farmers.

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Apart from the technologies themselves, the investment, ownership and thus, the business model for these technologies should be adopted by the local communities or cooperatives.

We believe that this mutual inspiration can result in better nutrient handling, increased value creation and therefore better livelihood for farming communities in Africa.

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Recycling nutrients and reducing emissions to the Baltic Sea

Expert article • 3822

The Baltic Sea is one of the most polluted sea areas in the world, but there are large geographical differences. The Baltic Sea has over several decades been supplied with nutrients from agriculture, dioxin from sewage plants, wastewater from polluting companies and other substances from the many rivers that flow into the Baltic Sea.

The problems and action proposals are not new. Many initiatives already appear in the existing Baltic Sea Action Plan. Several regional strategies and improvements, have already been implemented. The biggest environmental challenge now is the discharge of nutrients, especially from agriculture. According to the Helsinki Commission HELCOM (2021) update, it is concluded that agriculture still has the highest reduction potential, and is currently the main contributor to the diffuse load of nutrients to the Baltic Sea. The problem is that large amounts of nutrients are being discharged into the water, especially nitrogen and phosphorus. This creates algal growth and depletion of oxygen on the bottom of the sea, which again affects the entire eco-system in the Baltic Sea area. Consequently, it will reduce water quality, have an impact on biodiversity, less fish to catch and potentially less eco-tourism in the coastal areas etc.

Despite, there already have been made improvement over the last 20-30 years due to major environmental efforts - there are still severe problems with oxygen depletion. Research collaborations have already taken place among Baltic Sea countries in the form of the BONUS program and other international collaborations between different countries. It is not only research projects across borders, but also across disciplines involving biologists, geologists, agricultural researchers and economists. Research indicates that both climate and nutrient input affect the sea in interaction - and a combination of higher temperatures and continuous release of nutrients will probably worsen the situation.

Saving the Baltic Sea still requires a committed effort to handle these challenges, as well as pollution from an increasing activity at sea, leaving plastic and abandoned fishing gear, trawling and other raw materials with noisy and polluting ship traffic. It is therefore, important to look at many factors and to act on them simultaneously. In this regard, there is a continuous need to assess the environmental and economic impact of different measures and to find the most cost-effective measures to be implemented in those areas.

In crop production, only about half of the nutrients in mineral and organic fertilizers are converted to harvested crops, thus better nutrient use efficiency is a key to a more sustainable production. Some nutrient recovery and reuse practices and technologies are already used in the agricultural sector and in wastewater treatment. However, there is still a need for improvements and further incentives to reuse nutrients.

Studies indicate that several, eco-technologies could potentially be economic feasible and reduce the use of finite resources while providing a number of co-benefits to the surrounding society.

Eco-technologies could for example include more efficient recovery and reuse of nitrogen and phosphorous from wastewater, struvite recovery and reuse from digested sludge, anaerobic digestion as well as biogas production and fertilizer production from manure. In addition, different precision farming technologies based on global navigation systems could enable farmers to optimize the distribution of fertilizers within the field.

However, a key question is how to prioritize? What impact does the various eco-technologies have on society – either local or regional, or does the potential benefits outweigh investment and operational costs? One way to deal with it is to find the most economic viable eco-technology solutions. Findings indicate that some eco-technologies for circulating nutrients from agricultural wastes could be economically feasible for the farmers but also for the surrounding society.

Studies dealing with nutrient recovery eco-technologies often focus on merely their market costs and benefits, such as investment and maintenance costs and the revenues from selling products on markets. However, there may also be other benefits. For example, a technology might initially be developed for recovering or saving nutrients in crop production, but it often has other unconsidered environmental benefits (services) from reduced eutrophication, such as more biodiversity, more options for angling and other leisure activities. These benefits are also valuable to the society.

As an example, the cost of recycled phosphorus is often higher than the market price of mineral phosphorus implying that farmers prioritize to use mineral phosphorus, which is a limited resource. By increasing the use of recycled nutrients today increases the option of sustainable food production in the future. There is a need to develop and implement more efficient technologies - but also a need to uncover all environmental and social benefits to the surrounding society from these technologies.

Sometimes, the economic feasibility decreases with increasing complexity of the technology or it may take longer time to adopt. The costs for point source-separation systems are often relatively high and the technology can be complex, although the benefits also can be substantial. Future studies should therefore further explore how sustainable eco-technologies could be implemented in the best way with the highest net-benefits. This would require better quantification of a broader range of co-benefits, hydrological modelling, longer time frame as well as adopting a systemic view that considers a broad spectra of benefits and costs. By doing so, it is possible to quantify multiple impacts not only investment costs and market benefits but also other benefits, risks, and local impacts stemming from different eco-technologies. This is important for making better incentives and policies to reduce and reuse resources safely in a sustainable way.

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Closing the loop - recovering nutrients from our wastewater

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Wastewater. We all produce it, and we'd rather not think about what happens after we flush the toilet, empty our bath or rinse toothpaste down the drain. But it certainly deserves our attention. Throughout the ages, faeces and urine have been seen as valued resources for agriculture (fertiliser) and industry (ammonia). Later, when health risks became apparent and other sources more available, usage gradually declined. Since the late 19h century, access to clean water and the implementation of sewerage are probably the largest contributors to improved human health and our cities are unthinkable without. Sewage treatment started to be systematically implemented in the 1950s and since then advances in technology resulted in progressively cleaner water, protecting human and environmental health.

The clean water is mostly discharged to the surface water, where it becomes part of the natural water cycle. This sounds like a circular solution, but with the wastewater a wealth of resources was flushed down the drain: organic matter, nutrients like nitrogen and phosphorus and essential elements such as zinc. We excrete the majority of nutrients consumed with our food, disposing them into our wastewater. Recovering these nutrients as fertiliser for food production would be truly closing cycles.

Currently the world economy relies on finite resources, concentrated in certain parts of the world. Phosphate rock is probably best known in this regard, but the same is true for potash ore and elements like magnesium or cobalt. With the air consisting for almost 80% of nitrogen, this may seem an infinite supply. However, the process used to harvest it relies on finite natural gas. Making use of the resources contained in our wastewaters is therefore not only a nice circular idea, it is a vital part in ensuring their reliable supply.

Most sewage treatment plants (STPs) are based on energy intensive aeration of wastewater, with biodegradation of organic matter yielding sludge and carbon dioxide. Nitrogenous compounds are converted into nitrogen gas emitted to the air, and phosphorus and metals are removed with the sludge. The fate of nutrients in sludge depends on the local sludge management practices. The most direct way to use at least part of the organic matter and nutrients from our wastewater is through applying STP sludge as a fertiliser. In some countries this is normal practice, whereas in others little or no sludge is recycled due to strict legal limits to reduce risks for human and environmental health.

In society, there is a growing awareness about pollutants and associated health risks. Sewage contains varying levels of 'classic' pollutants like pathogens and heavy metals, as well as contaminants of emerging concern such as pharmaceuticals, antibiotic resistance and pfas. In the transition towards integrated nutrient recovery from domestic wastewaters, appropriate management of pollutants should be taken into account, making sure that any associated health risks are acceptable.

The wastewater sector has been making significant progress in the development of nutrient recovery technologies, but implementation is hindered by economic motives. Installing and operating additional technologies requires extra funds, that are not compensated by selling the recovered nutrients. At the same time, market acceptance of recovered resources and the regulatory framework are only just developing. Scarcity and geopolitical dependence of finite resources are not yet reflected in fertiliser prices. When this happens, recovery becomes economically feasible.

Recovery can have additional benefits: at some STPs, the phosphate mineral struvite is recovered, preventing its uncontrolled formation in piping and equipment. The reduction in maintenance costs makes the practice cost-effective. Struvite recovery is a mature technology, and the EU fertilising regulation was adapted to include struvite as a possible fertiliser product component. The same is true for phosphates recovered from sludge ashes. The advantage of incineration is that most pollutants are destroyed, an attractive aspect for many stakeholders. However, this process only targets phosphorus, whereas the other nutrients are not recovered at all.

The difficulty with sewage is that this is a mixed flow of all kinds of domestic, commercial and industrial wastewaters, combined with storm water. Useful resources are diluted and non-domestic pollutants are added. For the most efficient nutrient recovery we should be aiming for resource recovery close to the source, in this case: the toilet. Examples of source-separated wastewater systems with resource recovery are found in for example Helsingborg in Sweden ('Oceanhamnen' and 'ReCoLab'), Ghent in Belgium ('De Nieuwe Dokken') and Sneek in the Netherlands ('WaterSchoon'). In the applied concepts, highly concentrated toilet wastewater is collected with low-flush vacuum toilets and treated for biogas and struvite recovery. Depending on the local legislation, the produced sludge can be further processed for use as a fertiliser.

Although our wastewater is not an everyday conversation starter for most people, it is clear we can't continue to 'flush and forget'. The nutrients in our wastewater are vital for the future of our agrifood system, so we might want to ask ourselves a few questions. How can we achieve integration of nutrient recovery in our society? What risks do we find acceptable, when using recovered nutrients? And maybe more importantly: what about the risks we face if we don't?

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