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# Circular nutrient solutions for agriculture and wastewater – a review of technologies and practices

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This paper summarizes key findings from a series of systematic reviews and comprehensive efforts to collate evidence and expert opinions on circular solutions for recovery and reuse of nutrients and carbon from different waste streams in the agriculture and wastewater sectors. We identify established and emerging approaches for transformation towards a more circular nutrient economy with relevance to SDGs 6 and 14. The paper cites the example of the Baltic Sea Region which has experienced decades of fertilizer overuse (1950s–1990s) and concomitant urban sources of excessive nutrients. Regulations and incentive policies combining the nitrogen, phosphorus and carbon cycles are necessary if circular nutrient technologies and practices are to be scaled up. Pricing chemical fertilizer at levels to reflect society's call for circularity is a central challenge.

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## Introduction

To feed the growing world population following WWII and to create the 'green revolution', chemical fertilizers were introduced at scale in the form of nitrogen, phosphorus, potassium and the necessary minor and trace elements in the late 1940s. This increased from 50 megatons of fertilizer per year in the early 1950s to over 300 megatons by 1990 [1]. The Haber-Bosch process to produce ammonia from atmospheric nitrogen (N) allowed for this mammoth increase in fertilizer production, but it also resulted in surplus N ($NO_x$ and $NH_x$) in the environment [2]. Keeping pace with N, phosphorus (P) was mined from sedimentary and igneous apatite sources at increasing rates also since the 1950s [3] so that its levels in the environment have also exceeded the safe planetary boundaries [4].

The widespread availability of affordable fertilizer [5] has resulted in its inefficient use [6] often resulting in surpluses of N and P in soil finding their way by runoff and leaching to water courses. The losses from 'mine to fork' for P reach up to 80% [7]. Unlike N which is renewable and extractable from the atmosphere, P is non-renewable, and the world's affordable sources are therefore finite [8]. The global distribution of commercial P-rock reserves [9] is dominated by Morocco with >70%, creating a potential situation where availability could be reduced much like the oil crisis of the 1970s. The EU imports >90% of its P with only one active mine in Finland (Siilinjärvi). This is why the EU has put P-rock and white P on the list of Critical Raw Materials [10] (https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en) in order to promote recycling and increased resource efficiency. Recent estimates show that P reuse by 2030 within the EU using established technologies and practices will be able to replace about 30% of the mineral P used on farmlands [11••]. This together with more efficient farming and food management practices could make possible a more circular P economy [12,13]. The circularity of N and P in order to reduce losses and increase efficiencies is therefore at the centre of this review.

The management of carbon (C) is also part of this review. As organic matter, it plays a central role in soil fertility and structure (e.g. by increasing the water holding capacity). Like N, C is renewable and takes on various forms in organisms, water, soil and air. The circularity of C is indeed a prerequisite to building the circular economy [14] since this relates to energy, agriculture and urban systems. Biogas (methane) is a commercially significant carbon product from anaerobic digestion of organic wastes and along with it allows for the recovery of N and P from the resulting digestate (liquid and solid) which can also be used as a biofertilizer [15]. Globally, only 2% of the potential biogas production from organic sources (such as agriculture and food wastes and wastewater sludge) is currently being exploited [15]. Biogas has therefore great future potential to be a commercial driver for closing the loop on C, N and P.

The other major driver for closing this loop is the need to address the enrichment of water bodies by excessive nutrients (eutrophication) which often results in excessive algal blooms, deteriorated water quality and anoxic conditions. The mechanisms causing eutrophication have only recently been explained as P-limited freshwater systems and N as well as iron-limited marine systems [16–18]. Activities to manage eutrophication of regional water bodies and seas has taken on major proportion in various parts of the world [19] and particularly the Baltic Sea Region (BSR). The BSR represents a test case for SDG 6 (safe wastewater treatment systems) and SDG 14 (managing excess nutrient flows causing eutrophication) since much of the developments in terms of policy development, cross-border cooperation, and technical innovation within the BSR can provide an example for other regions of the world to learn from.

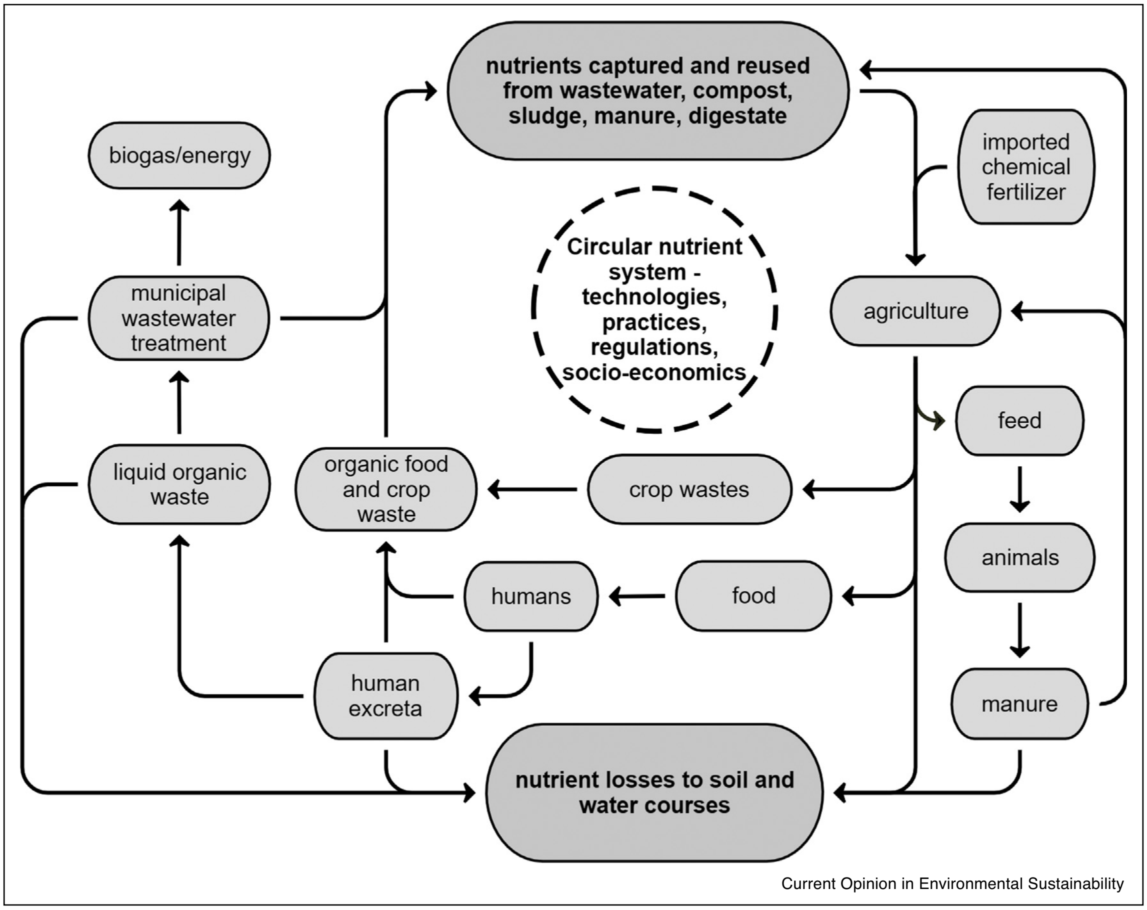
The Baltic Sea Region comprises nine countries with a total population of about 90 million within the drainage area which is about four times the 420 000 $km^2$ surface area of the sea [20•]. The BSR received excessive inputs of chemical fertilizer to support agriculture until the early 1990s [21••]. Although the use of chemical fertilizers has decreased over the past 30 years and wastewater treatment has significantly reduced point source emissions, the levels of dissolved- and total-P in the open sea continue to increase [22••]. The reason for this is twofold: legacy P from previous years of fertilizer use continues to enter the sea via runoff, and there is internal loading of P from anoxic benthic sediments which are rich in phosphorus [21••]. Also spreading of manure on farmland based on N crop requirements results in significant P overloading because stored manure contains reduced N to P ratios [23]. These loading sources are further aggravated by the fact that the Baltic Sea Proper is enclosed with a water residence time (time required for one volume change) of 25–40 years [24]. As a result, the (brackish) Baltic Sea is eutrophic with seasonal large-scale neurotoxic cyanobacterial blooms and extensive persistent hypoxic sediments. These cyanobacteria can fix atmospheric N rendering them P-driven [25]. These blooms import at least as much N from the atmosphere as is introduced from anthropogenic land-based sources (ca 370 000 tons per yr) [26]. Given that the improvements in water quality are slow [27,28], technologies have been developed and promoted to recover and reuse surplus N and P from land-based sources in the Baltic Region [29•]. This review stems from the Bonus Return project (https://www.bonusreturn.eu/) which has examined technologies and practices to capture and reuse N, P and C compounds from different waste sources and land-based activities — before they are lost to overloading and runoff. This work has combined findings from literature reviews, systematic maps and expert opinions. The project also reviewed economic assessment tools [30] and market barriers and opportunities that affect the development of innovative solutions for nutrient and carbon reuse [31]. The project conducted two systematic maps that described and collated evidence from the academic and grey literature published between 2013–2017 on technologies and practices for reuse and recovery of nutrients and carbon applied to wastewater [32–34] and agricultural waste [29•,35]. The mapping exercise of agricultural technologies resulted in 177 studies describing 25 recovery and reuse technologies in boreo-temperate regions. For the wastewater sector, 476 studies conducted globally described 28 reuse and recovery technologies.

## Overview of viable circular solutions: technologies and practices in the agriculture and wastewater sectors

Despite the increasing threat to our life support systems caused by excessive P, N and C ‘waste’ emissions [4] there are various technological solutions that can be applied to both the agriculture and wastewater sectors to recover and reuse resources in global food and energy production systems. We have observed in this work that many of the technologies can be used for both animal manure and sludge derived from sewage treatment plants and since the ultimate goal is to produce fertilizer and energy products, the two sectors could be better integrated in terms of strategic use of resources. Indeed, this is one of the aims of the EU Circular Economy Package of policies (see Section ‘Policies, markets and governance - barriers and opportunities for circular solutions in the Baltic Sea Region’). Figure 1 describes the elements of the circular nutrient system for the agriculture and wastewater sectors and the context within which the capture and reuse opportunities exist.

Within agriculture, reusing as soil amendments the ‘waste’ products arising from farming such as manure, crop residues, digestates, other organic materials and leachates is rather standard practice [36–38]. Wastewater on the other hand has traditionally been approached as a waste requiring treatment in order to reduce negative impacts before it is released back into the receiving water system [39]. Reuse, historically, has not been a design objective in wastewater treatment. A notable exception is the common practice in some developing countries where untreated wastewater is used on croplands as a source of both water and nutrients [40,41]. P in wastewater is traditionally removed using flocculating agents like aluminium or iron sulphate and iron chloride [42]. The floc

**Figure 1**



Overview of the constituent components of the agriculture and wastewater sectors that comprise the circular nutrient system.

produced if spread as sludge on farmland is not easily available to crops so alternative processes have been developed. These include P uptake by bacteria in activated sludge and P precipitation through the addition of, for example, calcium hydroxide (to produce calcium phosphates), or magnesium (to produce struvite) or potassium struvite. Struvite, which is receiving extensive attention, has the benefit that it contains some amounts of N in addition to the P [43–45]. Excess N in wastewater is traditionally reduced to volatile N gas by exploiting the biological process denitrification which occurs under anaerobic conditions [46] and is therefore lost. N recovery can however be achieved through ammonia stripping, and adsorbed to an acid, producing ammonium sulphate fertilizer [45,47].

A summary of common and developing technologies and practices for recovery and reuse in agriculture and wastewater is presented in Table 1 with a more detailed version in the online Appendix in Supplementary material (10.1016/j.cosust.2020.09.007). For agriculture, the list is dominated by the technologies that use manure as a recovery substrate [29•] but many of these are also now being used to work with sludge from wastewater treatment plants. These include anaerobic digestion, biogas production, struvite precipitation, ammonia stripping, membrane filtration, (vermi)composting, solid-liquid manure separation and drying, pyrolysis, bio-coal from hydrothermal carbonization, algal cultivation and various soil amendments. Agriculture practices that result in reduced runoff losses include the use of cover crops to trap nitrogen, planted buffer strips, artificial wetlands, sedimentation ponds and contour ploughing.

Reuse of manure, crop residues, digestates and compost on croplands requires extra attention if we are to see improvements in nutrient reuse efficiency. To optimize crop yields with these reuse products, farmers focus mainly on the N content. The challenge is to apply enough N and P to match the requirement of the crop. Since these products need to be stored prior to reuse they can lose part of the N content (via ammonia and nitrate

**Table 1**

**Introductory overview of technologies and practices from the agriculture and wastewater sectors to capture and reuse nutrients and carbon. A more detailed version of this table is found in the online Appendix in Supplementary material (10.1016/j.cosust.2020.09.007)**

| Technology/ practice | Description | Examples of results from selected studies |
|---|---|---|
| Anaerobic digestion | Anaerobic digestion can be applied to different organic substrates, including sewage sludge and manure, to produce biogas. The liquid effluent is a concentrated source of nutrients that allows for efficient capture using other technologies, such as struvite precipitation or ammonia stripping. The solid product, often referred to as biosolids, is commonly used as a fertilizer on agricultural land. | During evaluation of anaerobic digestion of swine manure, methane production potential was found to be dependent on manure source and storage time [48]. Long-term experiments found that differences in uptake of metals and organic pollutants were small when compared to mineral fertilizer, although the fertilizer efficiency was found to be somewhat lower [49]. |
| Struvite precipitation | This involves precipitation of equimolar amounts of P and N from various waste streams through additions of magnesium at high pH. The product, struvite, is an efficient P fertilizer that comes with the side benefit of containing some N. | Struvite precipitation was shown to achieve almost complete P recovery when applied to liquid anaerobic digestate of both sewage sludge (95–100%) [50] and manure (93–100%) [51]. Struvite was found to be an effective fertilizer when compared to mineral P fertilizer [52]. |
| Other methods for P precipitation | There are several precipitation methods for P recovery from various waste streams. Examples include precipitation of calcium phosphates and potassium struvite. | Potassium struvite precipitation was found to achieve up to 96 % P removal when applied to WWTP centrate [53]. Hydroxyl calcium phosphate precipitation was found to achieve 70% recovery of P when applied to domestic wastewater [54]. |
| Ammonia stripping | This involves stripping of gaseous ammonia from various waste streams at high temperature and pH. The stripped ammonia can be absorbed to an acid to create a low pH fertilizer, for example, ammonium sulphate, which is fit for soils with neutral or alkaline reaction. | When applied to a mixture of source-separated urine and liquid anaerobic digestate, ammonia stripping was shown to achieve 70–95% N removal [55]. |
| Pyrolysis | Pyrolysis of sewage sludge or manure is carried out to produce a coal-like substance termed biochar, which contains carbon as well as P and to some extent N. The resulting biochar can either be applied to soils or burned for energy. In the latter case, P can be extracted from the ashes. | When applied to swine manure, pyrolysis was shown to achieve almost complete (92–97%) P recovery. Pyrolysis of manure was found to be cost-efficient when compared to manure transport [56]. In addition to containing nutrients, biochar produced from sewage sludge has been shown to reduce leaching of nutrients from soil [57]. |
| Hydrothermal carbonization | Similar to pyrolysis, hydrothermal carbonization of sewage sludge or manure is performed to produce a coal-like substance, referred to as biocoal. As with biochar, biocoal can be either used for soil amelioration or burned for energy. | The soil amelioration qualities of both biocoal and biochar were found to vary depending on the process conditions of the production processes [58]. |
| Microbial bioelectrical system | Microbial bioelectrical systems can be used for the removal and/or recovery of nutrients and energy in various ways depending on configuration. | Removal of organic matter by up to 80 % was achieved using a microbial fuel cell setup fed with a mixture of municipal wastewater enhanced with synthetic nutrient solution [59]. When current was applied using electrolysis with a fluidized bed cathode, 70–85% soluble P removal was achieved [60]. |
| Algal cultivation | Micro- and macroalgae cultivation can be incorporated into various steps of waste treatment processes to capture nutrients. The energetic value of the algae can be recovered in different ways, for example through anaerobic digestion or hydrothermal liquefaction. | Microalgae were found to achieve 97% removal of both ammonia and P from urine [61]. Hydrothermal liquefaction of microalgae grown in municipal wastewater was found to capture 68% of the energetic value of the algae as oil [62]. |
| Cultivation of cover crops | Cultivation of cover crops is used to capture nutrients and reduce N leaching from soil. | The potential of cover crops to reduce N leaching was found to be strongly dependent on management practices such as time of planting and selection of crop species [63]. |
| Other agricultural practices | There are many agricultural practices that can reduce losses of nutrients from croplands. Examples include planting of perennial grass, shrubs and trees in buffer strips, use of constructed wetlands and construction of sedimentation ponds to trap nutrients in runoff. | Constructed wetlands including duckweed cultivation were found to be an effective measure for treatment of dairy waste [64]. |

losses) resulting in N/P ratios lower than what the target crop requires. So in trying to match the N requirements of the crops, excessive amounts of P end up being applied to fields [23]. This excess P is absorbed by most soils and can result in saturation of the upper layers after several years [21••]. Runoff and soil erosion remove some of this excess P. Nitrate is much more mobile in soil than phosphate and finds its way into groundwater and runoff causing pollution problems of major significance particularly in marine systems that are N-limited [65]. So reuse of waste materials from agriculture has both pros and cons from an environmental impact point of view, depending on the practices and whether the receiving water systems are P or N-limited. Practices in agriculture need to focus on both N and P use efficiencies in order to reduce soil nutrient surpluses [66], through reducing livestock density and utilizing soil P reserves more carefully [67].

## A review of economic tools and measures relevant to capture and reuse of nutrients

Once a technological solution for nutrient management, recovery and reuse is identified, a set of economic tools and analyses to support the decision on whether to proceed can be applied [30,68–70].This includes determining the economic efficiency of technologies, and the identification of social and private benefits and costs. Moreover, a wider range of economic criteria triggers and hinders the adoption of reuse technologies [30]. Data on economic efficiency of the reviewed technologies and practices have been added to the Appendix Table in Supplementary material (10.1016/j.cosust.2020.09.007). Case specificity and variable externalities make it difficult to draw broad conclusions regarding individual technologies and practices. The following section is therefore a less empirical overview of the state of knowledge regarding the economics of capture and reuse of nutrients.

### The economic determinants of implementing technologies

Whether or not a technology is economically feasible is determined by its cost, the market demand and price for the recovered and competing products, and also levels of energy consumption [68,70–72]. Yet, technologies may be economically feasible for one or few individuals but not necessarily for others. Feasibility from an overall societal perspective thus relates to both monetary and non-monetary impacts [68]. For instance, environmental benefits such as greenhouse gas mitigation, eutrophication alleviation or waste diversion result in benefits for society [69]. Considering these social benefits in economic assessments and decision-making is therefore recognized as making recovery technologies more beneficial, compared to the conventional alternatives [70,71].

### A typology of economic assessments

In the context of assessing the economics of technology development and implementation, the most commonly applied approaches are Cost-Benefit Analysis (CBA), Cost-Effectiveness Analysis (CEA) and Techno-Economic Analysis (TEA). The focus of these assessments is usually on private, direct costs related to technological implementation and maintenance. In the literature, however, there is no consensus on how different assessment approaches should be conducted in terms of which impacts should be included or neglected [30]. While not explicitly standardized, TEAs commonly focus on comparing multiple technologies and examining the expected private cost of technologies in the context of the quantified yet not monetized physical outputs, such as the relative cost of $CO_2$ capture [73], wastewater treatment [74] or agro-waste treatment [75]. Similar to TEA, CEA is conducted to provide a ranking of the relative performance of different technologies. The approach sets the cost of a technology in the context of the quantity of recovered products [76] or the resulting environmental improvements, for example, in water quality [77]. By focusing on how these outputs may be recovered with the lowest cost, CEA can therefore be considered as an output-oriented assessment. One of the most often applied tools for assessing technology feasibility is CBA [30] which is a widely accepted method for evaluating policies and projects [78]. CBA collects social costs and benefits of an intervention (e.g. a project, policy or technology) into a bottom-line, the net present value (NPV). Yet, although the importance of considering and accounting for environmental and social consequences is widely recognized [68,71,79], the quantification and monetization of such wider cost and benefits is complex and shaped by a high degree of uncertainty. Thus, studies often abstain from monetizing non-market costs or benefits and refer to CBA when addressing only tangible impacts, that is, private costs and benefits [80].

### Tools, measures and regulations to recycle nutrients

There are several tools and measures that can be used to save or help recycle nutrients. Which solutions to choose depends on the context in which the technology is applied and on local circumstances. It may often make sense to combine different measures and tools to establish more sustainable nutrient recycling practices.

When recovery technologies are not economically superior to the conventional alternatives, it may be necessary to apply instruments encouraging producers to uptake new technologies. A distinction can be made between regulatory, economic and information-based instruments [81]. For instance, volumetric fees or taxes on nutrients will reduce the demand for N and P and provide an incentive to create a shift that replaces the demand with more capital-intensive and nutrient-saving technologies. Yet, the effectiveness of a levy or tax depends on the level and the price elasticity of the nutrient [81].

Quotas can ensure that a certain amount of nutrients get recycled for certain purposes as it simply sets a limit for the overall use. A non-tradable quota can be a way to control the overall reuse of nutrients in a region. However, it is often difficult to manage because it requires that an authority can monitor the production. Another concern with non-tradable quotas is that nutrients will not necessarily be used and allocated in the most cost-efficient way. Tradable quotas could allow for a more efficient allocation of nutrients. Moreover, the quota price will reflect the marginal utility of that nutrient. An overall problem with quotas, both tradable and non-tradable, is that natural circumstances like increased precipitation may affect the total volume of wastewater produced limiting the use of quotas to manage nutrients sustainably [82].

A fixed fee on nutrients is often easy to manage and can be used to finance and maintain an efficient recycling technology. However, it seldom creates an incentive to save or recycle nutrients unless followed by some regulation on recycling. Producers tend to use additional nutrients once they have paid for the rights to use them. Subsidies to invest in nutrient-saving technology is another solution that provides an opportunity to implement more advanced and nutrient saving and recycling systems. This solution could however be relatively costly for society and it may not give producers an incentive to save nutrients unless there are specific regulations [82].

Direct regulations imply that added fertilizer, treated wastewater or agricultural runoff are only allowed in certain locations, or certain times of the year. One example is the use of planted buffer zones around streams and lakes and sensitive habitats to reduce runoff losses [83]. It could also set rules about the amount of manure or wastewater that must be used for biogas production in certain areas. If the supply chain is already in place with biogas facilities or wastewater treatment facilities, nutrient use savings and recycling could then be improved without further capital requirements.

## Policies, markets and governance – barriers and opportunities for circular solutions in the Baltic Sea Region

Different factors determine a successful management shift towards nutrient and carbon recovery and reuse technologies. These include regulatory, organizational, technical and economic factors that can be both opportunities and barriers [68]. Here, we give an overview of the major barriers and opportunities for circular solutions for recovering and reusing nutrients in the BSR.

### The complexity and interplay of EU regulations

Within the EU, nutrient and waste management within land-based activities is a heavily regulated field with a diversity of directives and regulations. These are summarized in Table 2. When striving for a more circular nutrient economy this multiple regulatory framework translates into both barriers and opportunities for technological innovation, implementation and uptake of new technologies and reuse/waste-derived products [31]. Most nutrient management policies have focused on reducing nutrient loads into receiving water bodies to limit eutrophication, and not returning the nutrients to productive use. The agriculture sector sees nutrients as fertiliser, while on the other hand, the wastewater sector sees them as pollutants [3]. This dichotomy hinders circular and integrated solutions and collaboration across the sectors [84]. In addition, due to farm specialization and the geographical mismatch between livestock farms and crop production systems, manure can be lacking in some cropland areas and in excess in animal husbandry regions [85].

Traditionally within the EU, animal manure, farm compost and sewage sludge have been applied as fertilizer (soil amendments). Essentially, no other organic fertilizers have been promoted by EU regulations as standalone sources and these have been seen only as potential sources of chemical feedstock to the fertilizer industry. This, however, is expected to change following the 2019 EU Fertilizing Products Regulation (https://data.consilium.europa.eu/doc/document/PE-76-2018-INIT/en/pdf) which might open the market for new and innovative organic fertilisers. This is expected to level the playing field for reuse fertilizer products, although not all such products are recognised in the regulation. Included is the issue surrounding natural cadmium (Cd) in industrial phosphate fertilizers derived from sedimentary P-rock [86]. P recycling in agriculture and wastewater provides an opportunity to produce fertilizer feedstocks with lower levels of Cd.

The Nitrates Directive at present limits the use of animal manure on agricultural land (170 kg N per ha per year), whereas application of conventional fertilisers does not have a strict upper limit [87,88]. The management of P in agriculture systems remains characterised by fragmented decision-making in national and regional administrations [89] where there is a lack of active regulatory support including recycling obligations, quotas or incentives. An exception is the 2017 development around N and P management in large pig and poultry farms (IPPC BATs, Table 2). On the wastewater treatment side, both N and P are also regulated through the Urban Wastewater Treatment, Sewage Sludge and Water Framework Directives (Table 2).

### Need for more regulatory harmonisation

N and P behave differently in the environment. Phosphate tends to bind to soil particles and organic compounds while nitrate is more mobile. As a result, the two nutrient groups cannot be managed in the same way. The EU Nitrates Directive has put the focus on N reuse in agricultural systems and P loading has not been managed in the same way. On the other hand, when it comes to wastewater treatment, phosphate has received most attention due to its dominant role in eutrophication in freshwater systems [16]. Preferential removal of P in wastewater treatment plants has cleaned up freshwater rivers and lakes (where P limits algal production) but has allowed the neglected nitrate to become a major source of eutrophication in marine coastal areas (where N limits algal production) [90]. N and P therefore need to be regulated together, also looking at combined approaches to capture and reuse.

**Table 2**

**EU Directives affecting N and P management in the agriculture and municipal wastewater treatment sectors**

| Item | Relevant regulated sector | Additional information and relevance to reduction and reuse of land-based nutrients |
|---|---|---|
| Circular Economy Package: http://europa.eu/rapid/press-release_IP-18-6161_en.htm<br>New Fertilising Products Regulation: https://data.consilium.europa.eu/doc/document/PE-76-2018-INIT/en/pdf | Agriculture, municipal wastewater | Today only 5% of bio-waste is recycled. Currently, the EU imports around 6 M tons of phosphate per year but could replace up to 30% of this by extraction from sewage sludge, biodegradable waste, meat and bone meal or manure. Promotes the use of bio-wastes as potential sources of fertiliser. CE control and marking to ensure safety. |
| Nitrates Directive 1991/676 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01991L0676-20081211&from=EN | Agriculture | Regulates amount of manure and fertilizer N that can be put on farmland (170 kg N/ha/yr); includes nitrate vulnerable zones (NVZs); manure phosphate is indirectly managed due to co-occurrence but can result in P overloading especially when using stored manure that has lost N |
| Common Agricultural Policy https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cap-glance_en | Agriculture | The renewed EU Common Agricultural Policy (CAP) for 2020–2027 (https://ec.europa.eu/commission/presscorner/detail/en/MEMO_18_3974), includes an obligatory nutrient management tool to improve water quality. To promote this, an app for farmers (Farm Sustainability Tool for Nutrients, FaST) has been developed (https://ec.europa.eu/info/news/new-tool-increase-sustainable-use-nutrients-across-eu-2019-feb-19_en). In addition, each member state will develop Eco-schemes to support and/or incentivize farmers to observe agricultural practices beneficial for the climate and the environment, beyond their mandatory requirements. |
| Groundwater Directive 2006/118 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:372:0019:0031:EN:PDF | Agriculture, forestry, industry | Nitrate is the main focus; phosphate has been added since 2014 |
| Waste Framework Directive 2008/98/EC https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN | Municipal solid waste | Includes recovery and recycling targets of waste products to reduce hazardous emissions and recycle substances of value; target for 2020 is 50% recycling of selected materials in municipal waste |
| Waste Incineration Directive https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32000L0076&from=EN | Urban & food processing organic wastes | Covers the incineration of bio-waste which is defined as biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants. It does not include forestry or agricultural residues, manure, sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood |
| Animal By-products (ABPs) Regulation https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R1069 &from=EN | Agriculture | Over 20 million tons of ABPs are produced annually from EU slaughterhouses, plants producing food for human consumption, dairies and as fallen stock from farms. ABPs can spread animal diseases (BSE) or chemical contaminants and can be dangerous to animal and human health if not properly disposed of. EU rules regulate their movement, processing and disposal. |
| Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006R1907&from=EN | Chemical industry; reuse products from wastewater & agriculture | Regulation of chemicals to protect human health and the environment. Linked to European Chemical Agency (ECHA) in Helsinki. Regulation of reuse products eg struvite. |
| Industrial Pollution Prevention and Control Directive BATs (Santonja *et al.* [110]) | Large pig and poultry farms | Provides limits for N and P emissions as well as best practices for manure management. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC107189/jrc107189_01_irpp_bref_07_2017.pdf |
| National Emissions Ceilings Directive https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016L2284&from=EN | Agriculture and industry | Regulates air quality standards. Relevant to emissions of $NO_x$ and $NH_3$ promoting safe storage of manure and capture of nitrogen. |
| WaterFramework Directive 2000/2000 https://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF<br>Quality Objectives 2015/2021/2027 | Municipal wastewater, agriculture, forestry, industry | Involves river basin management plans (RBMPs) aimed at maintaining good water quality. Strives to reduce nutrient losses in order to maintain water quality and prevent eutrophication - making the Baltic Sea a major target. |
| Sewage Sludge Directive (86/278/EEC) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31986L0278&from=EN | Municipal wastewater | Promotes use of treated sewage sludge in agriculture |
| Urban Wastewater Treatment Directive https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0271&from=EN | Municipal wastewater | Promotes the treatment of wastewater and thus the production of sewage sludge |

The EU directives that help manage nutrients from wastewater and agriculture therefore require better harmonisation, something that the EU Circular Economy Package [91] is attempting to do. This has created an opportunity for reuse of nutrients including P, which was added to the EU Critical Raw Materials List in 2014 (https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en). However, such policy visions are still waiting to be mainstreamed nationally, locally and among consumers [31]. Public awareness remains low regarding nutrient management and environmental impacts of dietary preferences, for example, the high proportion of meat and dairy products in European diets [92,93].

The Baltic Sea is a prime example exhibiting the need for better harmonised nutrient directives and policies. The regional body, HELCOM, which is dependent on voluntary implementation by Baltic Sea member states, has introduced several policy instruments [94] that go beyond the EU directives. These have set maximum allowable N and P emission targets for each country which has resulted in decreased inputs since the 1990s. Still, the total N input to the Baltic Sea in 2015 was about 7% larger than the maximum advisable HELCOM level, while P input remained 44% above that value [95]. Reduction of N and P in wastewater effluents and increased recycling of P from sewage sludge has also occurred [96].

### Sludge reuse for food production: perceptions and implications

When it comes to using sludge as a fertilizer for food production, social acceptability remains a barrier originating from taboos about using human excreta in agriculture [97]. In addition, there are both proven and perceived risks for heavy metals and pathogens, causing farmers to abstain from spreading raw sludge on croplands [85,98]. There is thus a growing resistance to the use of raw sludge as a soil amendment. Germany and Switzerland introduced a ban on this but at the same time they increased the requirement to recycle P from sludge. This will likely result in the solution to use mono-incineration and subsequent P extraction from the ash. Sweden may be considering a similar ban (see recent inquiry of the Swedish government: (https://www.regeringen.se/48e7cd/contentassets/3d68880d2e6942f3a1dccb158e46beb7/hallbar-slamhantering-sou-20203). While the sludge reuse ban in Germany and concomitant rules for P recovery provide clarity for technology developers, the result may be one single type of technology leading to lock-in for several decades. This could risk crowding out of other promising options which capture both P and C and may have less climate impacts than incineration [31].

### Markets for new technologies and reuse (waste-derived) products

To enhance market development of new technologies that can reduce nutrient losses, recycled nutrient products need to be included in fertiliser regulations. Assessment of nutrient reuse technologies regarding economic and environmental aspects still have not received adequate attention [31]. Wastewater systems, characterized by infrastructure with long-term investment horizons create stagnancy to change and hinder the development of nutrient recovery products for reuse [99,100]. This sort of lock-in is also affected by attitudes that large centralized systems are superior and more efficient compared to small-scale and decentralized systems [97]. Environmental externalities related to the production of conventional fertilisers are currently largely unaccounted for in price-setting, which can motivate the introduction of either governmental subsidies of waste-derived fertiliser products or taxation on conventional fertiliser products to increase incentives for reuse [31]. This could be important since the low market price of conventional fertiliser is identified to have contributed to the low profitability of reuse products on the market [84,92]. Regulations have been set up for conventional mineral fertilizers, making it difficult for reuse products to fit in due to variability in composition and production methods, plus lower product concentrations [87].

### Business models for innovative circular systems

New business models using, for example, a cluster system with increased collaboration between wastewater treatment plants (a source of reusable nutrients), fertilizer companies (a potential client for reusable nutrients), and farmers (potential end-users of recycled nutrients) are needed if circular nutrient systems are to be successfully implemented and upscaled [101]. Farmers and the fertiliser industry require a constant and predictable product meeting expectations for nutrient content and N/P ratio [85,87,92,102]. This also includes nutrient solubility and plant availability for reuse products [13], which do not always match those of mineral fertilizers. Volumes and steady supplies are also critical factors for making waste-derived fertilisers more attractive to the fertiliser industry and farmers [84,92]. Standardization and benchmarking across parameters such as consistency, safety, fertiliser substitution value, and added value benefits (e.g. low cadmium and additional nutrient elements) will in many cases be needed [93,103].

## Discussion

There are several resource, environmental and societal benefits from carbon and nutrient recycling and this paper shows there are technologies and practices available for this to happen.

### Optimising capture and reuse of wastes and turning them into energy and fertilizer resources

Capture and reuse technologies represent opportunities to close the loop within the agriculture and wastewater sectors. The starting materials include manure, crop residues, digestates (liquid and solid), wastewater and sludge. Important factors that need to be prioritised in implementation are bioavailability of the products for fertilizer, the transportability of the products to markets and the ability for storage without losses of volatile N and C or water-soluble N and P. The technologies readily at hand include:

- anaerobic digestion of wet matter which has the added advantage of producing biogas and allows N and P capture
- aerobic composting of dewatered matter which will allow for mineralization of N, P and C increasing the bioavailability of the resulting fertilizer
- pyrolysis of dried matter designed to retain C in the form of biochar which also retains P content
- incineration of dried matter to produce ash for extraction of P (N and C are lost to the atmosphere)

### Agriculture practices that allow for retention of nutrients on land preventing runoff losses

There are several farming practices that allow for trapping of runoff and soil to prevent losses to water courses. These include:

- planting of buffer zones that can trap runoff water containing N and P
- constructed wetlands that absorb N and P in wastewater and runoff
- sedimentation ponds on farmland to trap suspended soil particles containing N and P
- contour ploughing to reduces runoff formation
- cover crops that can trap and fix N and thus prevent losses to the atmosphere and water courses
- planting of crops without manure additions in order to reduce residual P levels

At the same time, there are several issues that presently impede but could be reversed or modified in order to promote circular, more integrated solutions for sustainable and beneficial C, N and P management. These are summarized below.

### A fairer price that captures externalities to open the market to reuse fertilizers

Affecting the overall dysfunctionality of the nutrient cycles reviewed here including the whole aspect of creating more circularity, is the fact that conventional fertilizers are relatively cheap and are often not used efficiently. The steps from mining to the level of the food consumer incur losses running up to 80% for P [7] and even higher for the N system originating from atmospheric extraction [6]. Because of the relatively low unit cost of mining, extraction and production, the reuse products cannot compete. For both the agriculture and wastewater sectors, production of commercially competitive and effective fertilizer reuse products remains therefore riddled with economic hindrances since chemical fertilizers are priced without considering many externalities while the nature of reuse products is that externalities directly steer the final price. Implementation and scaling of the reviewed agriculture and wastewater technologies is steered to a great extent by commodity markets for the raw materials used in producing conventional fertilizers, for example, P-rock, methane (for ammonia production), potash, sulfuric acid, other chemicals and various fuels and energy sources. The reuse products have to compete then with relatively cheap fertilizers that are priced based on these scaled-up commodities.

### Economic tools to promote nutrient capture and reuse

The economics of capture and reuse of nutrients and carbon from agriculture and urban wastewater are central to determining the feasibility of scaling up promising technologies and practices. Whether or not a technology is economically feasible is typically determined by its cost, the market demand and price for the recovered and competing products, its transportability, and also levels of energy consumption [68,70–72]. There are economic and administrative tools that can help promote recapture and reuse (e.g. quotas (both tradable and non-tradable), fixed and volume-based fees or taxes and subsidies). Much depends on the context in which the technologies are applied, and at the end it becomes a political, public/private choice accounting for local circumstances and priorities. Combining different measures and tools can provide a more sustainable solution for all parties involved.

### Regulatory mechanisms: focusing too much on N has left P unmanaged

Within the agriculture sector, by concentrating on the N content of manure and crop N requirements, surplus levels of P in farm soil and watersheds have resulted. Stored manure has relatively low N/P weight ratios, 3:1 and less, while most crops require double that ratio, closer to 5:1 or 6:1 [104]. To meet the crop N requirements, farmers end up applying onto soils 5–10 times the crop P requirements, eventually leading to losses through seasonal runoff. The EU Nitrates Directive does not control this problem [66,105]. In the Baltic region some countries have national regulations for P application to cropland e.g. Sweden, Germany and Denmark's 'harmony rules' [106]. The EU Water Framework Directive also identifies areas sensitive to surplus P but this does not directly manage manure spreading on croplands. Also manure, a source of C, N and P is not evenly distributed geographically and is not easily transported to areas where it is needed [107]. So reuse requires accounting for capture technologies and further transformation of product (e.g. dewatering) in order to make transport logistics economic.

### Sovereign sources of P, biogas from sludge and manure and other drivers for reuse

Reuse of P is receiving attention www.phosphorus platform.eu with increased awareness surrounding potential shortages of imported P fertilizer due to geo-political factors. Securing sovereign sources of P has created increased interest in reuse. Also the risks surrounding exposure to cadmium (Cd) by using fertilizer from sedimentary P-rock (in which Cd occurs naturally at relatively high levels), are relevant to this discussion. P recycling in agriculture and wastewater provides an opportunity to produce fertilizer feedstocks with lower levels of Cd. Also the high priority to reduce greenhouse gases by capturing and reusing carbon in soils is an opportunity for reuse of organic material from agriculture and wastewater. Renewable energy in the form of biogas can be produced from sludge, manure and farm/food wastes. Digestates contain N and P and can be applied to cropland. Indeed, biogas can be seen as a fundamental driver to developing the circular economy and this has only begun since global production has reached only 2% of its potential [15]. Connected to all this is the legislation that has banned ocean dumping and landfills for the disposal of sludge and manure [108] thus forcing the development of alternative solutions such as capture and reuse.

### Linear and ‘silo’ thinking impedes progress towards circularity

Although the situation above justifies action on how we manage nutrient-rich waste streams, the EU directives and Baltic Sea HELCOM have been slow in promoting circular systems. These directives and recommendations suffer from decades of traditional linear systems management where resources once used are designed to produce waste for disposal [31]. The wastewater and agriculture sectors have polarised views on the definition of waste [3]. Namely, in agriculture, waste is seen as a resource, since farming commonly includes the age-old practices to reuse both manure and crop residues. Wastewater systems on the other hand are designed to treat and remove waste and produce safe effluents – making recapture and reuse a second priority. This polarisation in thinking often impedes implementation of circular, more integrated solutions between these sectors. There are also negative attitudes among farmers, the food industry, health officials and policy makers about spreading sewage sludge on fields because of unwanted contaminants, for example, pharmaceuticals, heavy metals and microplastics [109]. On the contrary, these concerns should be a signal to work preventatively upstream to reduce or eliminate these substances so circularity can be introduced. The Swedish work around certifying municipal sewage treatment plants for safe reuse of their sludge is such an example www.ieabioenergy.com/wp-content/uploads/2018/01/REVAQ_CAse_study_A4_1.pdf.

## Conclusions

A thorough review was carried out of technologies and practices that turn waste streams into valuable resources producing fertilizer and energy products. The main sources of this organic material are from farming activities (crop residues, manure, compost and digestates) and from wastewater treatment plants (sludge and digestate). These are processed into bio-fertilizers and chemical fertilizers, biogas, biochar and biocoal returning C, N and P as resources to the market.

Given that implementation of these solutions at scale can be hindered by limitations in market mechanisms, governance and current infrastructure, we explored the established and emerging technologies, EU legislation and economic assessments that could transform these sectors towards a more circular economy also adding the Baltic Sea Region as an example.

Expansion of the markets for reuse fertilizer products is hindered by the availability of relatively inexpensive chemical fertilizers. Implementation and scaling of the reviewed agriculture and wastewater technologies is steered to a great extent by global markets for the raw materials used in producing fertilizers. This ultimately affects the revenue and profitability of recapture/reuse processes and products since the recovered nutrients must compete to be economically feasible. However, there exist key societal drivers that can go beyond the market. For example, the need to increase sovereign sources of P has promoted P recovery and reuse. Also, the need to reduce greenhouse gases through renewable energy promotes the reuse of organic material in both agriculture and wastewater. The banning of ocean dumping and landfills to dispose of sludge and manure has already nurtured alternative solutions including reuse in other parts of the world as well. And as we have pointed out the need to save the oceans and water bodies like the Baltic Sea from eutrophication is a major driver in developing circular systems.

Policy and governance are central to transforming the agriculture and wastewater sectors towards increased circularity. The EU Circular Economy Package was adopted in 2018, but most EU policies and regulations are rooted in the age-old linear, resource to waste paradigm. P has yet to enter the EU Nitrates Directive to allow for harmonized reuse with N. P recycling within the EU and the Baltic Region remains characterised by fragmented decision-making in regional or national administrations. Regulatory interventions, such as recycling obligations and subsidies are still lacking in most countries. In the case of the Baltic region, HELCOM is a regional coordination body producing recommendations to control nutrient emissions from member countries, but a compliance protocol is still lacking. Harmonisation of legislation, meshing recycled P with existing N fertiliser regulations with support for new operators would enhance markets for technologies, reduce nutrient losses and safeguard European quality standards.

Regulations and incentive policies combining the N, P and carbon cycles are necessary if circular nutrient technologies and practices are to be scaled up. Pricing chemical fertilizer at levels to reflect society's call for circularity is a central challenge.

## Conflict of interest statement

Nothing declared.

## Short summary

Environment-friendly technologies and practices that capture and recycle nutrients and carbon from municipal wastewater and agriculture are reviewed and the economic, policy and market barriers and opportunities for upscaling circular solutions in the Baltic Sea Region are synthesized [29•,30,31,33].

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## Appendix Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: 10.1016/j.cosust.2020.09.007.

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