Phosphorus circular economy: cost-benefit analysis of promising phosphorus recovery technologies in the EU

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Preface

Over the years, through my studies, work, and everyday life, I've become really interested in waste. To me, there is something fascinating about what we usually consider as waste. After all, waste isn't waste until we decide it is, and everything in this world has an attached value (that humans decide). The realization that so many materials with great potential are just thrown away sparked my motivation to dive deeper into this field and try to contribute to research in this field.

My specific interest in phosphorus recovery began during my bachelor's in environmental engineering in Brazil. In a wastewater treatment class, I first came across the concept, and it made so much sense. I thought to myself why on earth isn't this the status quo? That stayed with me.

Working on this thesis has been a challenging but rewarding journey. If there's one thing, I've (re)learned throughout the process, it's that having a clear and solid method really is key. A well-structured approach is one of the main foundations of doing meaningful research, and I'm sure I will take this forward with me.

I want to deeply thank my mom, Gabriella, my dad, André, and my sister, Julia, for always being so supportive – always answering my calls, cheering me on, and lifting me up when I needed it. A big thank you as well to my amazing friends, Bernadetha, Bianca and Sharvari, who went through all the ups and downs with me. It made the whole process a lot lighter knowing we were in it together. I also want to thank Ian for showing me kindness when I didn't expected it.

Lastly, I'm very grateful to my thesis supervisor, Hans-Peter, for his feedback, and guidance throughout this journey. Their support helped me to grow as a researcher. I am glad I found a supervisor that was also interested in this niche topic of phosphorus recovery and recycling.

Abstract

Phosphorus (P) is a key element for life and an essential resource for agriculture and thus food security. However, the current state of phosphate rock extraction, its associated mineral fertilizer production, and application have disrupted Earth's biogeochemical balance. These processes have led to regional imbalances, with excessive P in some areas and severe shortages in others, while contributing simultaneously to resource depletion and environmental degradation. In the EU, the matter is complicated by the region's high dependency on P imports and limited internal production. With the EU's circular economy ambitions and considering also geopolitical concerns of the P issue, phosphorus recovery gains an important strategic role.

This thesis aims to investigate P recovery in the EU as a pathway to sustainable management and improved P and food security. EU-level policies and regulations that foster phosphorus recovery are analyzed and the most promising waste streams and technologies for phosphorus recovery are identified. Two cost-benefit analysis (CBA) are then conducted: one at the firm level, evaluating the effect of the selling price of P recovered products, and another at the societal level, which incorporates the monetization of environmental externalities.

Findings indicate that even though the EU is a global benchmark for phosphorus management, significant gaps exist in achieving phosphorus sufficiency and circularity. Among the assessed waste streams, sewage wastewater emerged as the most promising one for P recovery. The CBA reveals that the incorporation of environmental externalities and its monetization is a strategic path for EU P decision-making, as promoting P recovery without considering the environmental impacts of specific technologies may, in some cases, aggravate existing environmental issues. Lastly, economic instruments are pointed out as necessary and complementary to the current command-and-control policy to ensure more effective and sustainable phosphorus management in the EU.

Contents

1 Introduction

1.1 The phosphorus issue

Phosphorus (P) is an important base fertilizer for agriculture as it is an essential element for all living organisms. It has an indispensable role as it is a key component of genetic material (DNA and RNA) and cellular energy processes, making it fundamental for plant growth and development.

Until the late 19th century, agricultural phosphorus enrichment relied on organic sources such as animal manure, human urine, and guano (Brownlie et al., 2021). After that time there was a fast increase of industrial-scale production of mineral phosphorus fertilizers from phosphate rock, particularly after World War II, when those fertilizers became the dominant choice in global agriculture (Ashley et al. 2011; Brownlie et al., 2021; Cordell et al., 2009). Since then, phosphate rock (PR) extraction has grown rapidly, mainly to produce fertilizers. Currently, it is estimated that 95% of the mined phosphate rock is used for fertilizer production (de Boer et al., 2019).

Even though phosphorus fertilization is invaluable for agriculture, and therefore for global food security, this excessive use of mineral phosphorus fertilizers is interfering with Earth's ecological equilibrium. The planetary boundaries framework (Rockström et al., 2009a; b) defined a safe operating space for humanity in relation to Earth's biophysical processes. These processes have uncertain but crucial thresholds that, if crossed, could result in irreversible environmental changes. Nitrogen and Phosphorus cycles compose the "biogeochemical flows" planetary boundary. Furthermore, Steffen et al. (2015) propose a regional threshold for phosphorus in addition to the global one. The main worry about trespassing this planetary boundary is that it could lead to large-scale anoxia of oceans (global boundary) and widespread eutrophication of fresh water (regional boundary). According to Steffen et al. (2015) and Richardson et al. (2023), the global and regional phosphorus cycle thresholds have already been trespassed.

The global supply of phosphate rock also faces challenges due to uncertainties surrounding its future availability. There is uncertainty around the size of economically viable and high-quality global phosphate rock reserves (Cordell et al., 2009; Cordell & White, 2011; Van Vuuren et al., 2010). Moreover, though the consumption rate of phosphate rock is expected to increase in line with rising population, dietary changes (higher meat consumption per capita) and biofuels usage (de Boer et al., 2019), there is also uncertainty about how much it will increase. Because of these uncertainties and continuous new estimates of reserves and consumption, the longevity of phosphate rock reserves is unclear. However, there is more consensus among researchers in this area that this mineral is not at immediate risk of depletion, but there is a real risk of availability of low-cost and high-quality phosphate rock in the long term (Cordell & White, 2011; van Kauwenbergh et al., 2013; van Vuuren et al., 2010).

Geopolitical factors also complicate the issue. Six countries have 86% of the known phosphate rock reserves: Tunisia (3%), Algeria (3%), Russia (3%), Egypt (4%), China (5%) and Morocco and

Western Sahara (68%) (U.S Geological Survey, 2024) - Western Sahara is an occupied territory which claims independence from Morocco, with its natural resources significantly fueling this conflict (White, 2015). However, the reserves differ from production. Currently, 78% of the production of phosphate rock happens in five countries: Jordan (5%), Russia (6%), United States (9%), Morocco (16%) and China (41%) (U.S. Geological Survey, 2024). This means that many countries around the world rely heavily on imports of this mineral and thus rely on other countries to fulfil their phosphorus fertilizers needs. Therefore, in case phosphate rock becomes scarcer, there is a risk of supply problems and higher production costs (Van Vuuren et al., 2010). This could bring vulnerability to the food production of countries that have less or even no reserves of this mineral.

In the EU, there is a clear dependency on external PR sources (van Dijk et al., 2016). In the EU, only one member state has significant PR deposits (Finland), which amount to less than 3% of the total global deposits, and also production of PR, only 0.45% worldwide (Zhu et al., 2023). According to the European Commission (*Ensuring Availability and Affordability of Fertilisers - European Commission*, 2024), the EU relies on imports for 68% of its phosphorus fertilizer consumption. For these reasons, phosphorus has been in the EU Critical Raw Materials List since 2014 (European Commission, 2014). Therefore, in the EU context, phosphorus efficient use, recycling and recovery gains even more importance.

Another issue that stems from the extraction of mineral phosphorus and its use as fertilizer is the presence of chemical elements that are harmful for plant growth, animal and human health. The pollutants that are present in the phosphorus minerals are mainly cadmium or uranium, and in a lesser amount but still relevant are arsenic, chromium, lead, mercury, nickel, and vanadium (De Rider et al., 2012; Reta et al., 2018; Wiśniowska, 2023). Specifically, cadmium, uranium, chromium and arsenic tend to bioaccumulate (Brownlie et al., 2021), posing even greater risk for end of the food chain beings, i.e. humans. For cadmium, content limits in phosphate rock derived fertilizers already exist in European Union (EU) countries and in some other parts of the world (Brownlie et al, 2021; Ulrich, 2019). However, these regulations are reportedly not well enforced (Bigalke et al., 2017; Brownlie et al., 2021).

Therefore, there is a need to expand and diversify phosphorus sourcing for agriculture, diminishing the reliance on mineral fertilizers, focusing on renewable phosphorus and while making the system more efficient. Whiters et al. (2015) proposed the 5R framework for sustainable P use, which includes: (i) Re-align P inputs to requirements; (ii) Reduce P losses to water; (iii) Recycle P in bio-resources; (iv) Recover P in wastes; (v) Redefine P use in society with a focus on food systems.

Phosphorus recovery from waste streams is a promising alternative to address the phosphorus issue, as it enables the reuse of phosphorus while reducing unintended phosphorus flows from waste that would otherwise eutrophicate water bodies. Moreover, phosphorus recovery is aligned with circular economy principles, that highlight the importance of resource efficiency, waste minimization, and the reintegration of valuable materials into the production cycle. The opportunities for phosphorus recovery are found at every stage of the supply chain, on all the waste streams that contain phosphorus. Furthermore, many phosphorus recovery solutions exist but in practice they are rarely applied, mainly due to their high costs as compared to mineral fertilizers (Hukari et al., 2016; Kabbe et al., 2019; Matsubae and Webeck, 2019; Mayer et al., 2016). Therefore, competitive recovery technologies and policy instruments are needed to change the business-as-usual phosphorus use and disposal (Ohtake and Tsuneda, 2018).

1.2 Objective and research questions

This research aims to investigate the potential of phosphorus recovery in the European Union as a way to contribute to sustainable phosphorus management and enhance the region's phosphorus and food security.

The research questions are:

1. Do EU laws and directives incentivize or stimulate phosphorus recovery? If so, what are the specific provisions?
2. a) What is the most promising waste stream in the phosphorus cycle, and what associated phosphorus recovery technologies have higher environmental benefits when compared to the business-as-usual process for that waste stream?

   b) What are the recoverable amounts for the identified technologies?
3. Which technology performs better at firm level, when considering the various prices of the recovered phosphorus products?
4. Which technology performs better when considering social costs and benefits, besides the internal costs and benefits?

1.3 Methodology

Research Question 1 will be addressed by a literature review focusing on EU policies and regulations related to phosphorus recovery for fertilizer use, using academic databases, official EU documents and publications, and relevant books. The analysis will highlight requirements and incentives for phosphorus recycling.

Research Question 2 will be addressed through a literature review to identify the most promising phosphorus-containing waste stream and recovery technologies. The selection is based on readiness level, financial benefits, and real-life success. The recoverable amounts will be retrieved from literature.

Research Question 3 and 4 will be addressed by a cost-benefit analysis, assessing the benefits of the project's implementation (recovery technologies-waste stream combinations) with the business-as-usual scenario. The analysis will be separated into two. First, a firm level CBA will be done to understand the effect of the selling price of the recovered product on the economic viability of the selected technologies. This step will only consider internal costs and benefits. Second, a societal CBA will be performed, this time considering both internal and external benefits. The aim of this analysis is to include environmental externalities on the decision making process. Data will be sourced from literature, reports, and databases. The results will include a ranking of alternatives based on their net present value (NPV) ratios to identify the most societal viable phosphorus recovery options.

The discussion will include the evaluation of the role of economic instruments in the context of phosphorus recovery. Based on the results for the firm level and societal cost-benefit analysis and certain economic instruments (selection based on literature), arguments will be brought to discuss how and if these instruments can help in internalizing externalities.

2 Methodology

2.1 Definition of Key Concepts

In scientific literature important key concepts related to phosphorus circular economy are used interchangeably. Thus, it is important to define those that will be addressed in this thesis:

1. Phosphorus Recovery: “Phosphorus recovery refers to processes used to isolate high-quality P from organic matter into raw materials that can be used to make recovered P fertilizers, or materials for use in the chemical industries.” As defined by Brownlie et al. (2022a).
2. Phosphorus Recycling: “We define phosphorus recycling as the use of P from residue streams (e.g. manure, biosolids, food wastes) in the production of food (e.g. crops and vegetables) and non-food agricultural products (e.g. fiber and timber)”. As defined by Brownlie et al. (2022a).
3. Recovered Phosphorus Fertilizers: phosphorus fertilizer that was produced from a waste stream of the phosphorus supply chain by a phosphorus recovery technology. In this research, the focus is on technologies that make recovered P fertilizer.
4. Mineral Phosphorus Fertilizers: fertilizers derived from mined phosphate rock.

2.2 EU Laws and Directives for P recovery

A literature review will be conducted, following methods similar to those used by Hukari et al. (2016) and Zhu et al. (2023), focusing on key EU-level policies and regulations related to phosphorus recovery and circular economy. This method, although not as comprehensive as a systematic literature review, allows for a more focused and efficient examination of the most relevant sources.

The search for peer-reviewed articles, books and reports will be done using keywords such as "phosphorus recovery", "EU policy", “EU legislation”, "circular economy" and “recovered phosphorus fertilizers” in academic databases such as Scopus and Web of Science. The official EU communications, directives, and regulations related to resource recovery and circular economy will also be consulted. These will be accessed through the official EU websites and databases. The analysis of these documents will focus on explicit mentions of phosphorus recovery and recovered phosphorus fertilizers requirements and incentives. This focused approach will provide a current overview of the most relevant EU frameworks on the topic of phosphorus circular economy and recovery.

2.3 Selection of Most Promising Waste Streams-Phosphorus Recovery Technologies

To understand which waste streams in the phosphorus cycle and associated recovery technologies will be selected to be further analyzed, a comprehensive literature review will be done. Recent peer-reviewed articles and technical reports will be consulted in academic databases like Scopus and Web of Science. Key words like "phosphorus recovery", "phosphorus waste streams", “phosphorus cycle”, "recovery technologies", and "recovered phosphorus fertilizers" will be used for this search.

Initially, the focus will be on identifying the major phosphorus-containing waste streams (e.g., wastewater, animal manure, food waste) as well as understanding the potential of recovery of this element as a fertilizer. Masso et al. (2022) described the phosphorus flows in agricultural systems, and Spears et al. (2022) mapped the phosphorus flows between the key parts of the global P cycle. Building upon the methodologies used in these studies, a similar analysis focused specifically on the EU context will be conducted. Based on the findings of the waste streams containing phosphorus, some of them will be selected to be further analyzed regarding the potential recovery technologies.

Following the decision on the waste stream, more desk research will be done to first have an overview of the possible phosphorus recovery technologies. Then, some of them will be selected for further economic analysis. The technologies will be selected based on parameters such as technology readiness level (TRL), reported environmental benefits, recovered phosphorus products that could be readily used as fertilizer and existence of full-scale applications. This approach will ensure the selection of the relevant and environmental beneficial technologies for further economic analysis in the context of phosphorus recovery from waste streams in the EU.

Finally, the recovery efficiencies of the technologies and the phosphorus content in the waste stream will be identified by using secondary data from literature. Data will be sourced from peer-reviewed articles, technical reports, and case studies.

2.4 Cost-Benefit Analysis of Phosphorus Recovery Technologies for the Selected Waste Stream

Based in results from Chapter 4, the selected waste stream was domestic wastewater. After the research from the previous chapter, the selected technologies for the selected waste stream will undergo a cost-benefit analysis (CBA). This section will thus specify and describe the steps to be taken to conduct this analysis, following general principles of CBA from Boardman et al. (2018) and Romijn and Renes (2013).

<u>Purpose of the CBA</u>

The first aim of the conducted CBA is to understand the effect at firm-level of the selling price of the recovered phosphorus product on the overall net benefits of the selected technologies. This choice was made to further Egle et al. (2016) analysis. This is a reference paper that evaluated 19 phosphorus recovery technologies from municipal wastewater and its results have been used by multiple relevant papers in the field (Achilleos et al., 2022; Chrispim et al., 2019; Ghosh et al, 2019; Law and Paguilla, 2018; Martin-Hernandez et al., 2024; Muys et al., 2021; Patyal et al. 2023; Rashid et al., 2020; Zhou et al., 2019). The study’s quantification of the recovered products was through a nutrient content method. This was pointed out to be a weak point of the study because it doesn't exactly hold in real life, but most of the recovered products didn't (and still don't) have a proper market so the selling price is an uncertainty.

The second aim of the conducted CBA is to understand which technology that has higher net social benefits. Based on literature research, the environmental impacts that come from undergoing these phosphorus recovery projects will be quantified and monetized (as external benefits), to show the overall economic value of implementing these technologies beyond just firm-level costs and revenues.

Baseline Scenario

The baseline scenario is the typical Waste Water Treatment Plant (WWTP) for domestic sewage in the EU. This WWTP will be determined based on literature research.

Alternative Scenarios

The alternative scenarios are the implementation of the selected recovery technologies in the typical municipal WWTP in the EU. The choice of analyzing an operating WWTP was made because EU sewage treatment is quite developed, and the region has a stable to slowly growing population. Moreover, the recast amendment to the Urban Waste Water Treatment Directive determines that a reuse and recycling rate of phosphorus should be set at Union level (EPC). Therefore, it makes sense to assume that current WWTPs will have to undergo modifications to be able to recover P and make use of it (thus recycling it). Thus, adjusting a WWTP to implement phosphorus recovery is more probable than the construction of a new one.

Internal Costs and Benefits

The costs to be examined include capital expenditures (CapEx) for installing recovery technologies, such as reactors, as well as operational expenditures (OpEx) related to, for example, energy consumption, labour, chemicals, and maintenance. The benefits can be split into two: internal and external. The internal benefits are those that project owners will effectively receive, such as selling the (recovered) fertilizer, co-benefits (e.g. energy production), tax reduction and subsidies. This CBA will consider the calculated costs and benefits in Egle et al. (2016), which considers only internal costs and internal benefits, that is, the costs that incur directly on the firm.

External Impacts and Costs/Benefits

The external costs/benefits are the negative/positive consequences that arise from the project that have no financial consequences to the project developer (negative/positive externalities), expressed in monetary terms. The first step to obtaining these values is the quantification of the impacts of the project implementation (alternative scenarios). This will be done through literature research. This study will only consider the environmental impacts. Moreover, given that the technologies selection will be based on reported environmental benefits, there will only be external benefits.

To translate the quantified environmental impacts into monetary terms, literature research on valuation of environmental impacts will be used. These include benchmark sources like the Environmental Prices Handbook EU28 (de Bruyn et al., 2018) and studies that include phosphorus recovery from wastewater and environmental valuation.

Correction of data for inflation

The collected data shall be corrected for inflation. First the inflation factor needs to be calculated (1), then with this factor, the adjusted price is calculated (2).

$$Inflation\ factor = \frac{Overall\ HICP\ index_{December\ of\ 2024}}{Overall\ HICP\ index_{December\ of\ Year\ of\ Data}}\ , \qquad Eq. (1)$$

where HCIP is the Harmonised Indices of Consumer Prices for the Euro area (European Central Bank, 2024).

$$Adjusted\ Price = Original\ Price * Inflation\ Factor \qquad Eq. (2)$$

Time horizon and Discount rates

The time horizon is set at 15 years, as this aligns with the commonly expected useful lifetime in construction engineering, unless specified otherwise (Egle et al., 2016).

The financial and social discount rates will be defined according to literature.

Net Present Value

Furthermore, all costs and benefits will need to be brought to the present value (PV), to reflect the time value of money, calculated by:

$$Present\ Value = \frac{Future\ Value}{(1 + discount\ rate)^{Year\ of\ Future\ Value}}\ , \qquad Eq. (3)$$

with discount rate determined through literature research.

Then, the Net Present Value (NPV) will be calculated, according to the formula below (Molinos-Senante et al., 2011):

$$Net\ PV = PV\ Internal\ Benefits + PV\ External\ Benefits - PV\ Internal\ Costs \quad Eq. (4)$$

If the NPV is greater than zero, it means the alternative projects have added benefits when compared to the baseline scenario. The higher NPV points out a more favorable alternative.

Sensitivity Analysis

Next, a partial sensitivity analysis will be done, to determine the robustness and reliability of CBA results prior to the final comparison and ranking of alternatives. This assessment will show how variations in key parameters - such as discount rates, recovery efficiencies, amount of people that the WWTP serves, market prices for recovered phosphorus and fertilizers, CapEx, and OpEx - impact the NPV and cost-benefit ratios of each alternative. These key parameters will be varied based on realistic ranges derived from the literature, and the resulting changes will be analyzed. With this step, the analysis further identifies the most influential factors on the social economic viability of the recovery technologies, and under which conditions the results remain valid or shift. This ensures that the final comparison and ranking are based on data that account for uncertainties, enhancing the validity of the study's conclusions.

Recommendation

The methodology will conclude with a final comparison and ranking of selected alternatives based on their NPVs, drawing also from literature to compare the results of this study with others.

Finally, more information on the methodology used can be found in Appendix A and B.

3 EU Supported Measures for Phosphorus Recovery

This chapter outlines the main regulations, directives and policies related to phosphorus recovery at the EU-level, encompassing direct mentions of this sustainable practice but also indirect ones such as sustainable nutrient management and related concepts. It is important to highlight the differences between these three types of government instruments. EU Regulations are legislative acts that are enforced automatically in all the Member States (*Types of legislation – EU,* [n.d.]). Whereas EU Directives, though also legally binding, establish objectives that member states must achieve, leaving it to each country to create legislations that will make them reach the set goals (*Types of legislation – EU,* [n.d.]). As for EU Policies, they provide strategic targets and frameworks, guiding the actions of the EU and its Member States. They are implemented by a variety of acts, from binding to non-binding ones, they include opinions, communications, recommendations, decisions, directives and regulations, from non-binding to binding acts (Hermann and Hermann, 2022).

3.1 Importance of policies and legal acts in this context

Policies and the legal framework are important guides to achieve government goals that lead to better social welfare, especially when concerning the environment (Kabbe, 2019). In the context of phosphorus, there is a clear need for new policies in areas where they are currently absent, as well as more effective and targeted policies where frameworks already exist, particularly due to the lack of economic incentives to shift from traditional mineral phosphorus fertilizers to those recovered from waste (Hukari et al., 2016; Kabbe et al., 2019; Matsubae and Webeck, 2019). Furthermore, scientists in this area acknowledge that progress on sustainable phosphorus management is not hampered by lack of scientific evidence or technological alternatives, but due to fragmented and lacking enforcement of policies (Brownlie et al., 2022b; Kalpakchiev et al., 2023), and of public awareness (De Boer et al., 2019).

Since farmers are the ones that will be using the recovered phosphorus fertilizers, they play a key role in accomplishing the circular economy of phosphorus. Therefore, their practices and wishes are very relevant in this context. Most farmers are used to using mineral fertilizers, thus having policies that foster the changing of this habit is important. Farmers are unlikely to change from mineral phosphorus fertilizer application to phosphorus rich organic materials and recovered phosphorus fertilizers unless they are assured to have equal or more profit. This shift can be fostered, for example, by subsidies or imposed by policies and regulations (Kleinman et al., 2015). Additionally, co-benefits associated with P cycling from organic materials, such as manure, can further incentivize their adoption. Moreover, the infrastructure, knowledge and tools related to mineral phosphorus fertilizers are more well-developed than recovered ones (Case et al., 2017), making it more difficult for farmers to shift from the former to the latter.

3.2 Current policies and legal acts in the EU

The oldest directive that is still in use is the Sewage Sludge Directive (European Directive 86/278/ EEC) (Council of the European Union, 1986). Its aim is to regulate the safe use of sewage sludge in agriculture and to increase it (Hukari et al., 2016; Zhu et al., 2023). This directive defines situations where sewage sludge can and cannot be used and sets limits for the content of certain heavy metals in sewage sludge (cadmium, copper, nickel, lead, zinc, mercury, chromium) (*Sewage sludge-European commission,* 2024; Hukari et al., 2016; Zhu et al., 2023).

The scope of the Urban Treatment Wastewater Directive (European Directive 91/271/ EEC) is to protect the environment from the adverse impacts of wastewater discharge, ensuring that domestic and industrial wastewater is collected, treated (removing organic matter, nitrogen, phosphorus and others) and discharged properly (*Urban wastewater – European Commission*, [n.d.]). It introduces restrictions of the discharge from WWTPs to sensitive areas (Hukari et al., 2016; Zhu et al., 2023). This directive was recently revised, with a proposal in 2022 and the setting of a provisional agreement at the beginning of 2024. The 2022 proposal includes making this sector energy neutral through diminishing energy consumption and producing renewable energy, focusing on biogas production, and establishing minimum recovery rates for phosphorus (*Questions and Answers on the new EU rules on treating urban wastewater*, [n.d.]). The 2024 provisional agreement includes a minimum combined reuse and recycling rate from urban wastewater and/or sludge to recover phosphorus.

The Nitrate Directive (European Directive 91/676/ EEC) objective is to protect water bodies from pollution caused by nitrates from agricultural sources, including farmyard manure, through good agricultural practices. Although this Directive doesn't directly mention P, many implementations of the directive by Member States have included P regulations. Most probably because N and P together are relevant for nutrient pollution, that is, controlling only N pollution and not P would probably not be as effective (Hukari et al., 2016; Zhu et al., 2023).

The Landfill Directive (European Directive 1999/31/EC) gives out rules for safety of waste disposal, which is inherently connected to pollution control. It was amended by Directive (EU) 2018/850 (European Parliament and Council, 2018). They set restrictions on disposing of all waste that is suitable for recycling from 2030 and set the limit that only 10% of municipal waste can be landfilled by 2035. Even though they don't directly mention phosphorus or nutrient management, these restrictions can help in improving phosphorus recycling from solid waste.

The Water Framework Directive (European Directive 2000/60/ EC) creates a unified legislative framework to protect inland, coastal, and groundwater through interconnected water management, pollution control, and sustainable use practices. As to what is mentioned in the directive that is directly related to P recovery and recycling, is that the substances that contribute to eutrophication (in particular, N03-N and PO4-P) are listed as main pollutants (Zhu et al., 2023).

The Groundwater Directive (European Directive 2006/ 118/EC) is about prevention and control of groundwater pollution and deterioration and puts phosphorus compounds on the monitoring list since the year 2014 (Hukari et al., 2016; Zhu et al., 2023).

The Waste Framework Directive (European Directive 2008/98/EC) addresses environment and health protection by giving basic waste management principles, such as the waste hierarchy, "polluter pays principle" and "extended producer responsibility" (*Waste framework directive - European Commission*, [n.d.]). Furthermore, it gives an important definition of "end of waste status" (Hukari et al., 2016; Carillo et al., 2024). This concept refers to when a material ceases to be considered as waste under EU regulations, because it has fulfilled specific criteria that make it appropriate for reuse, recycling, or recovery. Regaining product or "end-of-waste status" is the prerequisite for all materials to be allowed to be marketed in Europe as a product (Kabbe, 2019). In 2023 the European Commission proposed an update on this framework, in which the focus is textile and food waste. There is no direct mention of nutrient and/or phosphorus recovery and/or recycling in either the 2008 WFD text or the proposal of amendment.

The European Green Deal is the EU's strategy to deal with climate change and environmental degradation. Its aim is to transform the EU, by making it resource efficient while still with a competitive economy, making the EU climate neutral by 2050, with economic growth decoupled from resource use and being inclusive of all people and places (*The European Green Deal—European Commission,* [n.d.]). As part of this strategy, there are some sub-strategies, regulations and directives (new ones and revision or amendments to old ones) that are relevant in the context of phosphorus recycling and recovery: Circular Economy Action Plan, Farm to fork strategy, Zero pollution Action Plan, Critical Raw Materials Act, Political agreement on more thorough and more cost-effective urban wastewater management (*The European green deal—European Commission,* [n.d.]).

The Circular Economy Action Plan (CEAP) is one of the pillars of the European Green Deal. It aims to help with sustainable growth and climate neutrality by promoting resource efficiency and waste reduction throughout products life cycle through increased recycling and re-use (European Commission, [n.d.]).

The EU Fertilizing Products Regulation (2019/1009) (European Parliament and Council, 2019) was the first legal action from the CEAP (Hermann and Hermann, 2022), replacing the EU's former regulation on fertilizers (Regulation 2003/2003 EC). The new fertilizers regulation represented a big leap for nutrient recovery and recycling by setting rules for a unified European market for these products (Hermann and Hermann, 2022; Hermann et al., 2022; Carillo et al.,2024). The 'EU fertilizing products' were denominated by harmonized products (meaning that they follow the Fertilizing products Regulation and are thus eligible for free trade within the EU) or they are non-harmonized products, which means they follow the national regulations so they can only move in the national market) (*Circular Economy Action Plan - European Commission*, [n.d.]). The regulation also introduces standards on the fertilizer content of micronutrients (boron, cobalt, iron, manganese, molybdenum), macronutrients (nitrogen, phosphorus), pH, conductivity, heavy metals (cadmium, chromium, lead, mercury, nickel, arsenic), microorganisms, and organic carbon (Carrillo et al., 2024; Soo and Shon, 2024). This is specifically relevant for cadmium content limits, as the content of this element in conventional phosphorus mineral fertilizers are usually higher than recovered phosphorus fertilizers, thus this gives a competitive help for the latter (de Boer et al., 2019; Jupp et al., 2021; Hermann et al., 2022). Moreover, the regulation also defines new Component Material Categories (CMC) like digestates, animal by-products, struvite, biochar, and sewage sludge and its derived ash, making it easier to trade the CMCs in Europe (Carrillo et al., 2024).

Critical raw materials are those that have high economic importance for the EU and high risk of supply disruption to the EU (Council of the European Union, 2024). Since 2014, phosphate rock has been listed in the EU Critical Raw Materials (CRMs) (European Commission, 2014), while elemental phosphorus (P_4) was added to this list in 2017 (and has remained there until the present day) (European Commission, 2017). More recently, in March of 2024, the EU passed the European Critical Raw Materials Act (Regulation EU 2024/1252) (European Parliament, 2024). The Act's objective is strengthening these materials value chain, broadening import sources to diminish dependencies, improving the EU's ability to monitor and manage risks related to supply disruptions and enhancing circularity and sustainability (*Questions and answers on the European critical raw materials act*, 2023). Moreover, the European Commission highlights a focus on the raw materials that are used in the strategic sectors of renewable energy, digital, space and defense technologies and those that are expected to have a demand growth not compatible with the supply and difficulties in scaling up production (*Questions and answers on the European critical raw materials act*, 2023). However, out of the 34 materials on the list, only 17 are considered as strategic raw materials (SRMs) and neither elemental phosphorus nor phosphate rock were in this sub list. This is very relevant, as this new Regulation proposes more measures and clear targets specifically for SRMs, rather than for all CRMs. The European Sustainable Phosphorus Platform (ESPP) argues that purified phosphoric acid and elemental phosphorus should be in this list because they fit the EU's definition of SRMs (ESPP, 2023). Moreover, even though they are not listed as a SRMs, the act still supports phosphorus sustainability and recycling by demanding monitoring, encouraging circularity and streamlining permits for recycling projects (ESPP, 2024).

The Farm to Fork Strategy is another pillar of the European Green Deal. It aims to make food systems sustainable, socially fair and healthy (*Farm to fork strategy—European commission*, [n.d.]). The framework proposes a goal of 50% reduction in nutrient (Nitrogen and Phosphorus) losses to the environment (air, water, soil), while maintaining soil fertility, and 20% reduction in the use of fertilizers (*Questions and Answers: Farm to Fork Strategy - building a healthy and fully sustainable food system*, [n.d.]). This goal is also mentioned and set in the Biodiversity Strategy to 2030, the Farm to Fork Strategy and the Zero Pollution Action Plan (Grizetti et al., 2023). To address this target, the European Commission is developing with member states the Integrated Nutrient Management Action Plan (INMAP) since 2022 to reduce and hinder further nutrient pollution deriving from unnecessary use of fertilizers and to support recycling of organic waste to make fertilizers (*Questions and Answers: Farm to Fork Strategy - building a healthy and fully sustainable food system*, [n.d.]).

The new Common Agricultural Policy (CAP) of 2023-2027 (*CAP 2023-27 - European Commission*, [n.d.]) introduces eco-schemes, in which farmers who adopt or continue with sustainable agriculture practices can be rewarded for it (*Eco-schemes - European Commission*, 2024). The legal basis for the CAP's Strategic Plan, and thus also the eco-schemes, lies in the European Regulation 2021/2115/EC (European Parliament and Council, 2021). The regulation clearly states that nutrient management (specifically for phosphorus and nitrogen) is eligible for the eco-schemes: "prevention of soil degradation, soil restoration, improvement of soil fertility and of nutrient management and soil biota". However, it is worth mentioning that the regulation also states that each eco-scheme needs to include at least two of the areas of action mentioned, which cover climate, environment, animal welfare and combating microbial resistance, and that nutrient management is part of only one. Moreover, the regulation doesn't clearly mention that using recovered phosphorus fertilizers is considered to be a sustainable agriculture practice. It would, nevertheless, be important that it did that (Hermann et al., 2022). But this is open to interpretation. Although the regulation doesn't directly mention the use of recovered fertilizer, the CAP is in place also to support the European Green Deal targets and one of them is the 50% reduction of nutrient losses to the environment, which can partially be achieved by phosphorus recovery.

3.3 Critical analysis of the current policies and legal acts in the EU

In comparison with other parts of the world, the EU legislation and policy regarding phosphorus sustainability is currently the most progressive and comprehensive (Cordell and White, 2015; Matsubae and Webeck, 2019; Hermann and Hermann, 2022; Carrillo et al., 2024; Soo and Shon, 2024). Even though phosphorus management tools exist in the EU, P pollution is still a big issue in Europe, indicating that they are not sufficient, either because they are ineffective or not properly enforced or both (Masso et al., 2022). On top of that, the sustainable phosphorus measures are fragmented into multiple EU policies and laws, which complicate addressing this issue properly (Brownlie et al., 2022b; Masso et al., 2022; Soo and Shon, 2024). In addition, according to Garkse and Ekardt (2021), the current legal framework is highly made up of command-and-control laws, which come with governance problems like weak enforcement, rebound and shifting effects. Also, the Integrated Nutrient Management Plan, which had its public consultation closed in August of 2022, and was announced to be ready by the second quarter of 2023 (*European Commission - Nutrients action plan for better management*, [n.d.]) is still not ready. Therefore, multiple scientists have called for an integrated EU nutrient regulation or directive (Brownlie et al., 2022b; Masso et al., 2022; Wassen et al., 2022). This framework should have regional thresholds concentrations for N and P, because: (i) the ecological impacts are a result of a synergy between the presence of both nutrients and they are both basic components of fertilizers, being thus applied together in agriculture; (ii) some regions have too much phosphorus or nitrogen in the soil and others have too little, therefore regional thresholds are an important element to be considered (Wassen et al., 2022). Moreover, according to Wassen et al. (2022) the nutrient policies that limit the source of N and P spreading into the environment are more effective, rather than those that consider cumulative concentrations or their environmental effects. This new framework would be important to achieve the European Green Deal targets related to nutrient sustainability (50% reduction in nutrient - N and P - losses to the environment - air, water and soil - while maintaining soil fertility, and 20% reduction in the use of fertilizers).

However, it is important to also mention that some European countries have legislations that are in the direction of accomplishing the P circular economy (Zhu et al., 2023). For example, Switzerland will make P recovery and recycling from P-ruch waste streams mandatory it mandatory from 2026 onwards (Zhu et al., 2023). In Germany, a similar policy was adopted in 2018 that makes mandatory P recovery from sewage sludge for municipal WWTPs that serve more than fifty thousand people, which equals about 60% of Germany's plants, with a period of 12 years to achieve this goal (Hermann et al., 2022; Carrillo et al., 2024). In 2014, the Netherlands adopted a law that sets a non-time binding target of 25% of fertilizers being made from recovered P in the long term, that focuses on struvite (De Boer et al., 2018; Carrillo et al., 2024). This means that while there is no strict deadline, the Dutch government has an ambition to promote the production and use of recoverd phosphorus fertilizers (particularly struvite) as opposed to mineral fertilizers, to go towards sustainable nutrient management. It is important to highlight also that Germany's and the Netherland's regulatory framework is supported by the EU (Carrillo et al, 2024).

Another type of measure not directly supported by the EU are the platforms that promote phosphorus recycling and recovery, such as the ESPP. These platforms can play a synergizing role in facilitating phosphorus recovery by joining diverse stakeholders and fostering collaboration on new opportunities (Zhu et al. 2023).

3.4 EU Policy Conclusions

A broad package of regulations, directives, and policies that consider phosphorus management show the EU global leadership in the sustainable handling of nutrients as part of going towards circular economy. From the long-standing Sewage Sludge Directive and Urban Wastewater Directive to more recent work under the European Green Deal, including the EU Fertilizing Products Regulation and Circular Economy Action Plan, the EU has led on the sustainability of phosphorus compared with other global regions. However, despite this progress, significant challenges persist.

Most of the policies that exist are not integrated but fragmented, therefore less effective. The reasons include weak enforcement, governance gaps, and a lack of sufficient economic incentives for shifting to recovered phosphorus fertilizers. The absence of an integrated nutrient regulation or directive further complicates the efforts since ecological impacts from phosphorus and nitrogen are interrelated. Moreover, delays in finalizing the Integrated Nutrient Management Plan highlight that urgent action should be coordinated.

To attempt to resolve this issue, a single EU nutrient framework, including regional thresholds for phosphorus and nitrogen concentrations, accompanied by source-directed pollution policies, may significantly enhance phosphorus sustainability. Further economic incentives, better governance, and the stimulation of innovation in phosphorus recovery technologies will also be required to meet the environmental and circular economy objectives of the EU.

3.5 Need for global agreement on Phosphorus Management

An important issue to be addressed is the lack of a global intergovernmental agreement on phosphorus sustainability. Even though phosphorus is acknowledged as a global issue since 2011 – UNEP Year Book 2011 (Syers et al., 2011), important international initiatives often don't mention phosphorus, such as the Sustainable Development Goals (SDGs) and the Aichi Biodiversity Targets (Brownlie et al, 2022b). Not only that but addressing the phosphorus issue can synergistically help in achieving these initiatives goals (Kanter and Brownlie, 2019; Walsh et al., 2023).

Phosphorus is also a part of the planetary boundary of biogeochemical cycle, along with nitrogen. The planetary boundary framework identifies the environmental limits within which humanity can safely operate to avoid catastrophic environmental changes (Rockström et al., 2009a; b). The global planetary boundary of P has been surpassed on the first decades of the 1900s (de Vries et al., 2013), with it reaching eight times the limit in 2017 (Sandstrom et al., 2023). The primary concern with exceeding this planetary boundary is the potential for large-scale ocean anoxia (at the global level) and widespread eutrophication of freshwater systems (at the regional level). Moreover, even though there is heterogeneity in the P distribution around the world, with some being P-saturated and others being P-deficient, intergovernmental agreements would help in addressing the global phosphorus redistribution (Sandstrom et al., 2023).

Furthermore, global coordination with the setting of regional targets (Masso et al., 2022; Wassen et al., 2022) and the sharing of successful experiences in phosphorus policy and management are imperative for success regarding this topic (Masso et al., 2022). Intergovernmental agreements would be important to pressure nations into following the set goals. Therefore, scientists in the field have urged for measures to be taken regarding phosphorus sustainability. In 2019, over 500 scientists supported the "Helsinki Declaration" (*The Helsinki Declaration*, 2019), which is a call for global action on phosphorus sustainability, emphasizing phosphorus's critical role in food security and environmental health. Scientists urge measures like increased recycling, efficiency, and equitable access to phosphorus.

Finally, one can also argue that this is a human rights issue. Phosphorus is an indispensable element for global food security, agricultural productivity, and the fundamental right to food. As phosphorus is non-renewable and non-substitutable, it is vital to agriculture and the nutritional supply of the world's population. The rising and volatile phosphate rock prices (Brownlie et al., 2023), uneven global distribution, and insufficient global management of fertilization lead to areas with serious nutrient deficits, limiting food production, and regions that are overfertilized, resulting in environmental pollution that affects human health (Penuelas et al., 2023). This raises significant concerns about future access and affordability (Weikard, 2016), potentially violating the basic human right to food. Thus, addressing phosphorus sustainability is crucial for ensuring food security and for safeguarding human rights.

4 Phosphorus Waste Stream and Associated Recovery Technologies for Fertilizer Use

This chapter first presents the identification of the most relevant waste streams in the phosphorus supply chain, followed by which waste stream was found to be more promising for phosphorus recovery. Then, the possible technologies for this waste stream were analyzed and three of them were chosen to be further studied in chapter 5. Finally, the amount of P in the chosen waste stream and the efficiency of recovery of the chosen technologies were identified.

4.1 Possible waste streams to recover P

The main use of phosphate rock comes from fertilizer use, so it is no wonder that a great part of the phosphorus containing waste streams stems from subsequent steps of mineral fertilizers. Figure 1 shows the phosphorus waste streams in the phosphorus supply chain, with a focus on the mineral fertilizers flow as they correspond to 95% of what the phosphate rocks are used for (de Boer et al., 2019).

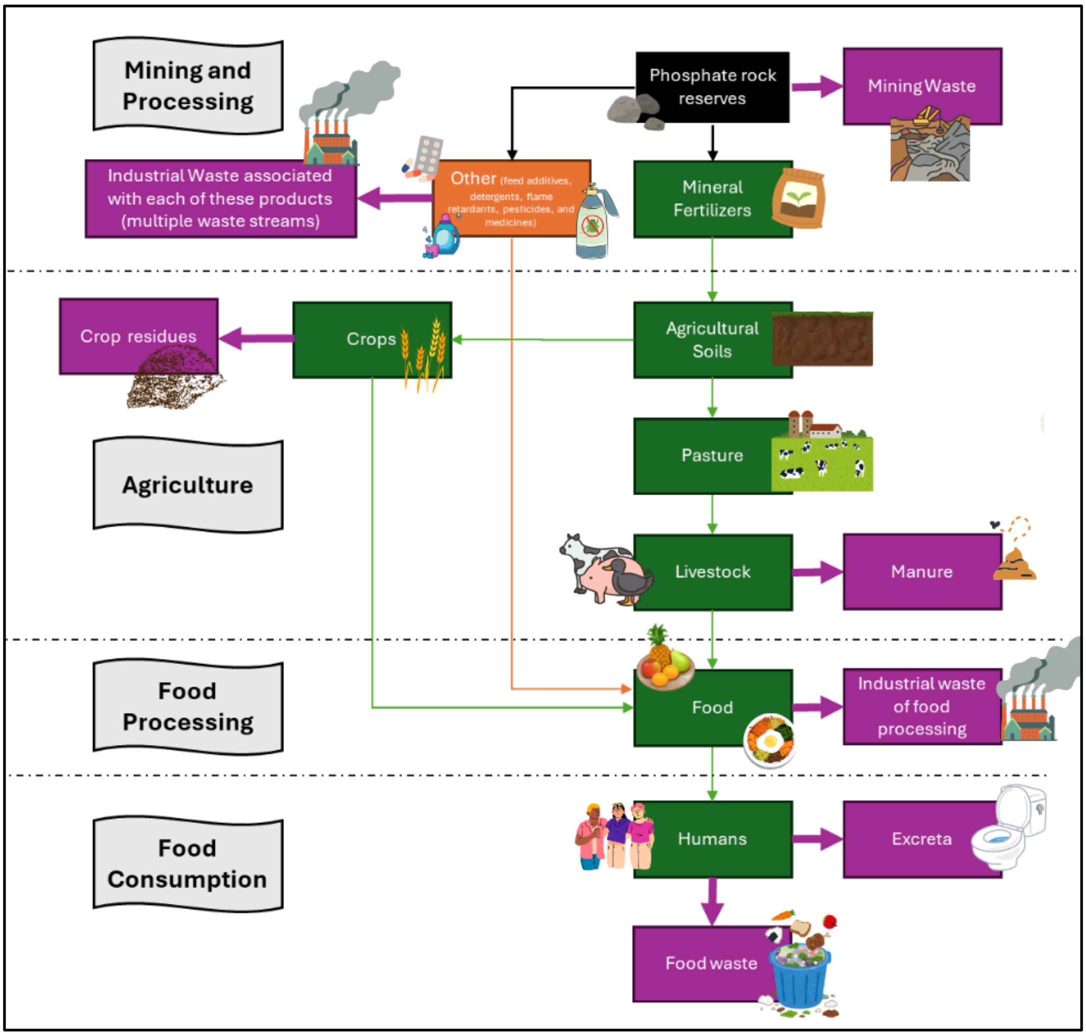

Figure 1. Simplified phosphorus flow focusing on the waste streams and excluding discharge to water bodies and recycling routes. Waste streams are represented in purple. Adapted from: Cordell et al., 2011; Spears et al., 2022; Masso et al., 2022; Zhu et al., 2023.

It is important to highlight that the figure excludes the discharge of the phosphorus waste streams into water bodies because the focus of this research is on waste streams that can be handled and not on recovering phosphorus from water bodies. However, it is important to remember that all of these waste streams tend to end up in water bodies if not treated and also that there is the occurrence of agricultural runoff of the mineral fertilizers that are put in the soil. Moreover, all waste streams have the possibility to be a source of phosphorus and be recycled.

4.2 Selection of waste stream to be analyzed

Scholz and Wellmer (2015) identified phosphorus has a low net use efficiency of about 5%, highlighting that any reduction of losses or increase in efficiency is significant to ensure long-term supply security. In the phosphorus supply chain, only 50-70% is transformed into beneficial products in the mining processing of phosphate rocks, meaning that 30-50% stays in mining waste (Scholz and Wellmer, 2015). Therefore, this is an important flow to be investigated from a circular economy perspective (Ohtake and Tsuneda, 2018). Whereas sewage has about 5% of global P flows (Scholz and Wellmer, 2015), with only a fraction of this going to wastewater treatment. Thus, looking from a mass-flow perspective it seems unwise to address this waste stream before the mining waste (Ohtake and Tsuneda, 2018). However, Ohtake and Tsuneda (2018) argue that phosphorus recovery from sewage is at the forefront of technological advancements, with emerging thermal, chemical, and biological methods showing potential to become economically viable alternatives to unsustainable practices like incinerating dried sewage in cement or coal power processes. Also, most of the available and developed phosphorus recovery technologies are for wastewater (Schipper, 2019). In addition, P recovery from wastewater has an advantage of strengthening phosphorus (and food) security because it is possible in regions with no mines, which is important in the EU context as only one member state has significant PR deposits (Finland, 3% of total global) (Zhu et al., 2023) and the region is, thus, dependent on imports (van Dijk et al., 2016).

According to van Dijk et al. (2016), the fate of phosphorus in waste in the EU-27 in 2005 was 1217Gg P, with 7%, 5%, 28%, 6%, and 54% coming from the crop production, animal production, food processing, non-food production and consumption sectors, respectively. Thus, the biggest waste came from the consumption sector, amounting to 655 Gg P (Figure 2). Out of the 655 Gg P lost in the consumption sector, the category that lost most of the P was communal sewage sludge 34.6%, followed by 12.2% from food waste from food service, 12.1% from food waste from households and 10.6% from pet excreta, with the other categories having less than 6% of the total loss of P. Moreover, the combined wastewater categories (blue) amount to 54.8% of the P loss in the consumption sector. It is important to remember that this paper analyzed the food consumption–production–waste chain and non-food flows, therefore the phosphorus wasted in mines was not considered.

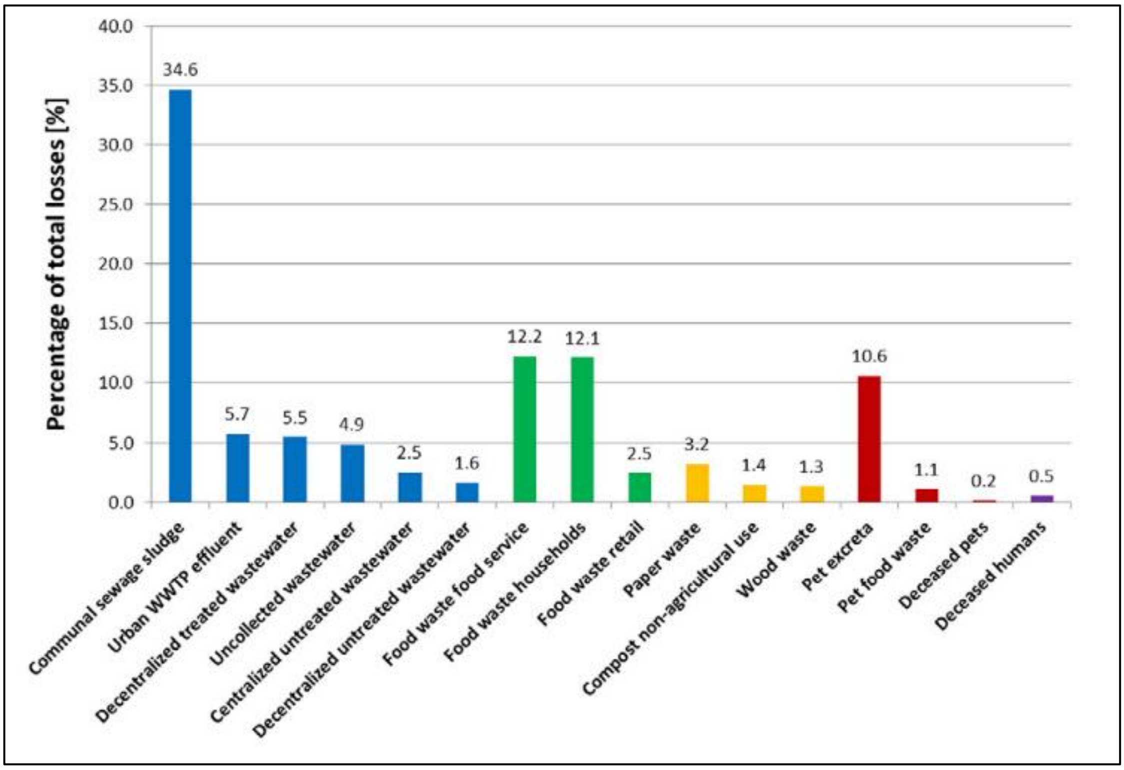

Figure 2. Share of phosphorus (P) quantities in solid and liquid waste flows lost from the consumption sector (totaling 655 Gg P) for the EU-27 in 2005; grouped by wastewater (blue), food waste (green), non-food organic waste (orange), pet related waste (red) and deceased humans (purple). Source: van Dijk et al. (2016).

The enrichment of waterbodies with nutrients from sewage wastewater is another reason why evaluating phosphorus recovery from wastewater is relevant. This is because about 50% of the phosphorus that arrives in waterbodies have sewage wastewater as their origin (Rout et al., 2021). And, eutrophication of water bodies is a pressing ecological challenge, that impacts aquatic ecosystems and potable water availability (Akinnawo, 2023) and therefore needs to be addressed.

4.3 Selection of most promising technologies for the chosen waste stream

As a first step in understanding phosphorus recovery technologies from wastewater, the description of general WWTP is needed. WWTPs processes progress from preliminary to primary, secondary, tertiary (also called advanced) treatment, with each higher level configuration of WWTP includes the preceding stages. Metcalf and Eddy (2013) define each treatment level as: (1) preliminary treatment removes large solids through grit chambers; (2) primary treatment partially removes suspended solids and organic matter, usually through sedimentation; (3) secondary treatment removes most of the organic matter and suspended solids, mostly through biological processes, though additional or alternative chemical processes can be applied, this step also includes some nutrient (phosphorus and nitrogen) removal; (4) tertiary treatment focusses on purifying water even further, including the removal of nutrients, heavy metals or micropollutants. Sludge treatment is also an indispensable process that is part of WWTPs, this is well described by Drinan and Spellman (2013). First, the sludge undergoes thickening. Then it is stabilized through chemical or aerobic or anaerobic digestion, the latter being most common and allowing for biogas recovery. These two steps improve handling, remove pathogens and organic content. Finally, the stabilized sludge is dewatered so that it can be disposed of somewhere (incinerated or landfilled).

Furthermore, it is necessary to understand the current state of WWTPs in the EU since it is the context of this study. Currently, 82% of urban wastewater is directed and treated by WWTPs (European Environment Agency, 2020). Those comprise of a total of 20,087 urban WWTPs, with 14,149 having biological treatment with nitrogen and/or phosphorus removal, 5,573 with only biological treatment and 365 with primary treatment only (Figure 3), equivalent to 535, 344 (64%), 140 (26%), 51 (10%) million p.e, respectively. According to the updated Urban Waste Water Treatment Directive, WWTPs are required to have different levels of treatment based on the amount of people of the urban area and sensitivity of the discharge zone (EPC, 2024). For those with more than 10,000 and less than 150,000 p.e., the discharge concentration should be minimally 0.7 mg P_{total}/l or the P removal should be at least 87.5%. For areas with more than 150,000 p.e., the discharge concentration should be minimally 0.5 mg P_{total}/l or the P removal should be at least 90%. For urban areas with less than 10,000 p.e., the requirements vary depending on more variables, but they are less stringent than the ones for bigger agglomerations. Moreover, the majority of WWTPs meet their target treatment levels, with an additional 8.3% and 7.5% coverage needed for biological treatment and biological plus nutrient removal treatment, respectively.

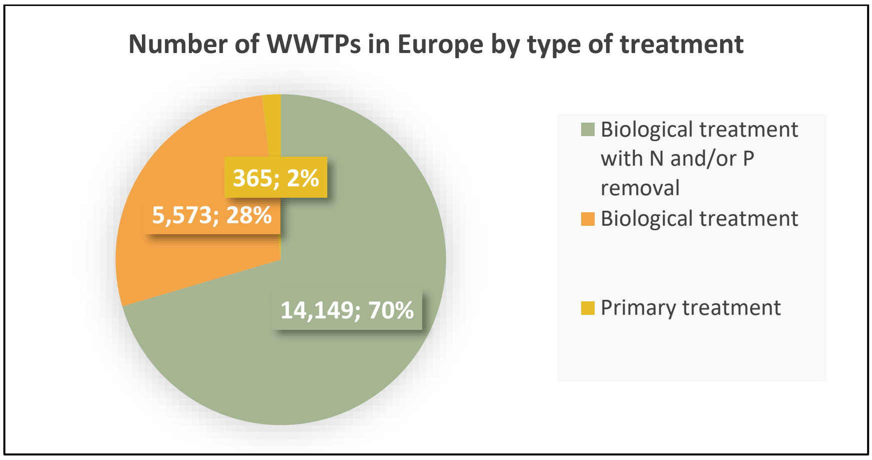

Figure 3. Number and Percentage of WWTPs per type in Europe. Adapted from European Environment Agency (2020).

Specific data for the different configurations of WWTPs in the European Union was hard to find. However, conventional activated sludge systems are the most common type and well-established type of secondary treatment plants (Kabbe, 2019; Metcalf and Eddy, 2013). Thus, it was assumed that this type of treatment is representative of real-life cases in the EU. Moreover, phosphorus removal in sanitation systems usually happens through biological accumulation in biomass (enhanced biological phosphorus removal - EBPR) or by chemical phosphorus removal (CPR) or a combination of both (Kabbe, 2019; Metcalf and Eddy, 2013; Minnesota Pollution

Control Agency, 2006; Rout et al., 2021). CPR happens through adding iron, aluminum or calcium salts, causing the precipitation of barely water-soluble phosphates that are then removed by filtration or membrane separation. CPR using iron and aluminum are the most common alternatives for achieving low content of phosphorus in the effluent (Metcalf and Eddy, 2013). Furthermore, adding iron is the cheaper option making it the usually the preferred option (Wilfert et al., 2015). The combination of EBPR and CPR also happens mostly with the addition of iron (Zheng et al., 2024). Also, according to Wilfert et al. (2015), the percentage of WWTP that had EBPR, EBPR with CPR and CPR was respectively 16%, 21%, 43% for Germany, 13%,51%, 32% for the Netherlands, 5%, 0%, 95% for the UK, and 17%, 36%, 47% for France. Moreover, according to the and Rout et al. (2021) these three types of phosphorus removal are the most common. Though the provided information is not that specific, it gives an indication of the current state of advanced phosphorus removal: most of it is done through CPR, then through EBPR combined with CPR and then only through EBPR. Therefore, the most common WWTP configurations in the EU are: (1) secondary treatment conventional activated sludge plants; (2) tertiary treatment conventional activated sludge with CPR through iron addition; (3) tertiary treatment conventional activated sludge with combined EBPR and CPR through iron addition; (4) tertiary treatment conventional activated sludge with EBPR; all of them with anaerobic digestion of sludge, and further thickening and dewatering. The first configuration of WWTP can be seen in Figure 4, the other configurations would have a similar flowsheet but for CPR there would be the adding of iron salts in one or multiple streamlines and for EBPR the aeration unit would be preceded by an anaerobic unit.

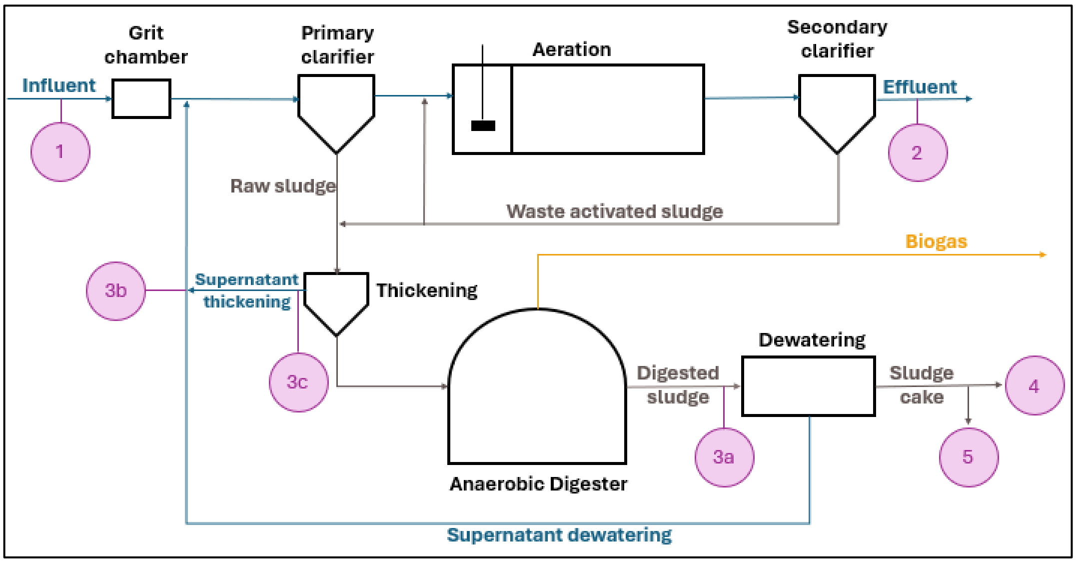

Figure 4. Typical flowsheet of a centralized wastewater treatment plant and where the selected P recovery technologies are installed. (1) urine separation; (2) secondary treated effluent; (3a) digested sludge prior to dewatering; (3b) sludge liquor after dewatering; (3c) liquor of thickened sludge; (4) agricultural application; (5) incineration. Adapted from Kabbe (2019) and Schaum et al. (2018).

An important parameter for this context is the phosphorus contribution to raw sewage per capita. It varies based on diet (amount and phosphorus content in food), use of personal care products (amount and phosphorus content in products), food waste (disposed in sewers), detergents and cleaning products, drinking water treatments, possible industrial inputs (Comber, 2013).

Literature estimates (Table 1) for total phosphorus content in raw sewage varies between 1.6 to 2.5 g P/person/day (Comber et al., 2013; Egle et al., 2016; Huber et al., 2020; Witek-Krowiak et al., 2022).

Table 1. Phosphorus content in raw sewage.

Total phosphorus in raw sewage (in g P per day per person)	Source
2	Comber et al. (2013)
1.8	Egle et al. (2016)
1.6 – 2	Huber et al. (2020)
1.8 – 2.5	Witek-Krowiak et al. (2022)

Another important parameter is the average flow of wastewater. A commonly used value is 150 or 200 liters per capita per day, as used by Comber et al. (2013), Egle et al. (2016). This value can also vary between 100 to 400 liters per person per day, based on populations life style, water price, water availability of the area, among others (Pikaar et al., 2022).

Phosphorus recovery from wastewater can happen in multiple places. These are at the source (through urine separation), in the secondary treated effluent, in the sludge or sludge liquors, through direct use of sludge by agricultural application and through incineration of the exiting sludge (Figure 4). A pre-requisite for urine separation is urine and feces separation at the source, which is not the case for European (and most) countries (Schaum et al., 2018). Thus, this option would require a big change, making it quite challenging. Secondary effluent application requires that specific phosphorus removal doesn't take place at the WWTP because it needs phosphorus to still be in this effluent and not concentrated in the sludge. Though this option is theoretically possible, there aren't any known real-life cases for this approach (Schaum et al., 2018). Direct agricultural application already happens but there are some caveats to implement this option. This method is in fact the most applied one to recycle P, being most times used as a nutrient supplement or soil-conditioner (Law and Paguilla, 2018), thus application of mineral fertilizers is still needed to improve the agricultural efficiency (Jupp et al., 2021). Moreover, direct land application of sludge has been having more and more restrictions in many European countries due to the bioaccumulation of heavy metals, trace contaminants, contribution to eutrophication and substances of growing concern such as pharmaceuticals and forever chemicals (Kabbe, 2019; Law and Paguilla, 2018). For example, in Belgium and Switzerland it is not legally allowed to input biosolids as fertilizer on agricultural fields due to food safety (Law and Paguilla, 2018), with Switzerland having a total ban on the application of sewage on farmland (Kabbe, 2019). Another example is eutrophication problems in Germany and the Netherlands, where there are too large on-farm waste streams that are being valorized, surpassing the area's capability to naturally absorb them and creating problems (Kabbe, 2019). These arguments explain why direct sewage sludge applications are not the most attractive alternative to be explored. Finally, the final sludge in WWTP with phosphorus removal concentrates about 90% of the influent P (Cornel and

Schaum, 2009; Kabbe, 2019), which is the case for most WWTP in the EU. Moreover, given that the bigger plants have bigger amounts of possible recovery of P, and that the bigger plants have a requirement of removing phosphorus, most of the phosphorus recovery technologies were developed to recover P from sludge/sludge liquor/sludge ash. Moreover, technologies that recover P from the sludge are known to be more effective. For these reasons, the focus will be on P recovery on sludge liquors or sludge inside the WWTP or through sludge incineration.

The technology for phosphorus recovery from municipal wastewater has two important classifications: phase of phosphorus recovery and applied process to extract the phosphorus. The phases to recover P are the liquid phase (wastewater and sludge treatment water), sewage sludge phase (raw and digested sludge), and sewage sludge ash phase (product of sewage sludge incineration) (Salkunic et al., 2022). For the processes, the most applied ones are crystallization/precipitation, wet chemical extraction, and thermochemical treatment, besides others that are still not widely applied and/or are still being further developed, such as membrane separation, nanocrystallization, adsorption, ion exchange and biological assimilation (Salkunic et al., 2022). Over 40 processes exist for phosphorus recovery (European Sustainable Phosphorus Platform, 2021) and new ones are still being developed, with commercial scale technologies focused on sewage sludge, digestate, abattoir wastes, poultry litter, manure, food processing and industrial wastes, mainly in the EU, Japan and North America (Brownlie et al., 2024; Hermann et al., 2022). The variety of available processes reflects the wide range of conditions under which phosphorus recovery is necessary (Hermann et al., 2022). Moreover, out of these technologies, 15 of them are applicable for sewage sludge ash, 22 for sewage sludge/digestate and 13 for liquor/aqueous phase (European Sustainable Phosphorus Platform, 2025).

Overviews of phosphorus recovery technologies from wastewater have been given in literature by Egle et al. (2016), Kabbe (2019), Sanchez (2020), Salkunic et al. (2022), Canziani et al. (2023), Patyal et al. (2023), Zhu et al. (2023) and Martin-Hernandez et al. (2024). Most of the established and full-scale technologies are for the aqueous phase of sludge through the precipitation of struvite (magnesium ammonium phosphate - $MgNH_4PO_4.6H_20$) that can recover 10-30% of the influent phosphorus. The reason for the advanced development of these technologies in comparison to other P recovery ones is that it addresses a serious problem that occurs in wastewater treatment: the formation of struvite in the anaerobic digesters, which causes multiple operational and maintenance problems (Metcalf and Eddy, 2013). This problem is common in WWTP employing secondary treatment and anaerobic digesters (Achilleos et al., 2022; Fattah, 2012) and it is particularly recurring in WWTP with EBPR and Anaerobic Digestion (Kabbe, 2019). However, P recovery from sewage sludge or ash can reach up to 90% of the phosphorus entering the WWTP, making this process also quite attractive. Vivianite [$Fe_3(PO_4)_2{\cdot}8H_2O$] recovery also shows promise, but further technical development and study is needed to understand this alternative better.

While these reviews (mentioned in the previous paragraph) provide valuable insights, there is a lack of comprehensive coverage, standardization and consistency. While many articles discuss certain technologies, they tend to overlook others. Additionally, each of these articles chooses their own way to convey information on the available technologies at the time of publication. The terminology is often vague, with some sources distinguishing between commercial, industrial, pilot, and laboratory scales, while others simply use the terms full-scale and small-scale. Moreover, information appears to be inconsistent (e.g. in Canziani et at. (2023) the TRL of EcoPhos is reportedly 7, whereas in Kabbe et al. (2019), an older publication, the TRL of this technology is 9, which logically doesn't make sense). All of this limits the ability to fully assess phosphorus recovery options.

Since one of this study focus is understanding the financial impact of environmental benefits, the technologies included in the cost-benefit analysis were chosen based on the available data on environmental impact, internal costs, and internal benefits, information that is provided by Egle et al. (2016) and Amann et al. (2018), where 19 of these technologies are evaluated. The selection criteria for the technologies are based on presence of environmental benefits when compared to the reference system and the recovered material being readily available for use as fertilizer. The environmental impact evaluation was taken from Aman et al. (2018). The first assessment of possible included technologies can be seen in Table 2.

Table 2. Possible Technologies (highlighted in purple) for Phosphorus Recovery from Wastewater On-Site. MAP - Magnesium ammonium phosphate *(struvite)*; CaP (Calcium Phosphates); GWP – Global Warming Potential; AP – Acidfication Potential. Adapted from Amann et al. (2018).

Technology	Recovered material	Recovery Potential in % of WWTP-influent	GWP (% change in relation to reference system)	AP (% change in relation to reference system)	Recovered material readily used as fertilizer?	Environmental Benefits?	Possibly Included?
REM-NUT®	MAP	45–60%	-5	-27	YES	YES	YES
Ostara Pearl®	MAP	10–max. 25%	-13	-24	YES	YES	YES
PRISA	MAP	10–max. 25%	-7	-24	YES	YES	YES
P-RoC®	CaP/MAP	10–max. 25%	5	-13	YES	YES/NO	NO
AirPrex®	MAP	10–max. 25%	-15	-21	YES	YES	YES
DHV Crystalactor®	CaP	10–max. 25%	37	44	YES	NO	NO
Gifhorn	MAP/CAP/FeP	35–55%	57	127	YES	NO	NO
Stuttgart	MAP/CAP/FeP	35–55%	70	154	YES	NO	NO
MEPHREC®	P-rich slag	~70%	8	3	NO	NO	NO
AquaReci®	Cap/FeP	~60%	93	67	YES	NO	NO
PHOXNAN	MAP	~40–50%	37	165	YES	NO	NO
AshDec® Cold Ash	Depolluted ash	~85%	-11	-63	NO	NO	NO
AshDec® Hot Ash	Depolluted ash	~85%	-16	-64	NO	YES	NO
PASCH	CaP	~60–70%	-2	-6	YES	YES	YES
LEACHPHOS®	CaP	~60–70%	-56	-55	YES	YES	YES
RecoPhos®	Mineral Fertilizer	~85%	-15	-19	YES	YES	YES
EcoPhos®	Phosphoric Acid	~85%	-12	-97	NO	YES	NO
Thermphos®	P4	~85%	-27	-47	NO	YES	NO

The primarily selected technologies are REM-NUT, Ostara Pearl, PRISA, Airprex, PASCH, LEACHPHOS and Recophos. To select the final technologies to be further assessed some criteria were used. First, having types of recovery technologies with different recovered products was a criterion. The recovered products from the short-listed technologies are struvite, calcium phosphate and mineral fertilizer. Between the struvite recovery technologies (REM-NUT, Ostara Pearl, PRISA, Airprex), the ones that performed better from Egle et al. (2016) economic analysis were Airprex, Ostara Pearl and PRISA. Moreover, Airprex and Ostara Pearl are more consistently mentioned and assessed in literature - Kabbe et al. (2019); Salkunic et al. (2022); Patyal et al. (2023); Sanchez (2020); Canziani (2023) for Airprex and Canziani (2023); Patyal et al. (2023); Egle et al. (2016); Zhu et al. (2023); Sanchez (2020); Sanchez (2020) for Ostara Pearl - than PRISA - only by Egle et al. (2016). Thus, Airprex and Ostara Pearl were the selected struvite recovery technologies to be analysed. Between the Pasch and Leachphos technologies, there is a big difference in their environmental impacts, with the latter having more environmental benefits than the former, when compared to the reference system. Thus, the included technology was Leachphos. The RecoPhos technology is the only one that has mineral fertilizer as the recovered product, so it was included in the final selection. To summarize, the included technologies were Airprex, Ostara Pearl, Leachphos and Recophos (Table 3).

Table 3. P recovery technologies selected to be analyzed. Adapted from [1] Canziani et al. (2023); [2] Egle et al. (2016), [3] Kabbe (2019), [4] Kabbe (2023), [5] Martin-Hernandez et al. (2024); [6] Sanchez (2020), [7] Salkunic et al. (2022), [8] Schaum et al. (2018), [9] Patyal et al. (2023), [10] Zhou et al. (2017), [11] Zhu et al. (2023).

Technology	Phase	Process	Output	Recovered P/ Influent P (%)	Scale	Source
AirPrex	Sewage sludge (digested sludge)	Precipitation/ Crystallization	Struvite	10-max 25%	Full-Scale	[1] - [10]
Ostara Pearl	Aqueous	Precipitation/ Crystallization	Struvite	10-max 25%	Full-Scale	[1] - [8], [11]
Leachphos	Sewage sludge ash	Wet-chemical extraction	Calcium phosphate	~60-70%	Full-Scale	[2] – [4], [6] -9]
Recophos	Sewage sludge ash	Wet-chemical extraction	Ash comparable with mineral fertilizer	~85%	Full-scale	[1] – [10]

4.4 Conclusions

Phosphorus can be recovered from mining waste, industrial waste of specific products that use phosphorus in their production, crop residues, manure, industrial waste from food processing, excreta and food waste. From these different waste streams, it was identified that in the EU the biggest potential for phosphorus recovery stems from wastewater. Phosphorus recovery technologies for wastewater are significantly advanced, with methods being close to achieving economic viability. Moreover, recovering P from this waste stream can also diminish EU's external dependence on phosphorus and thus increase phosphorus (and food) security in the region. Among the different types of wastewaters, sewage wastewater was identified as the one with the biggest phosphorus recovery potential and was thus the chosen waste stream to be further analyzed.

Multiple and diverse technologies for phosphorus recovery from sewage exist. Given data and time constraints, only some were analyzed. Among the technologies reviewed, struvite precipitation was the most implemented method, offering operational and financial benefits.

From the reviewed technologies, four full-scale phosphorus recovery technologies from sewage wastewater were selected and described, so that their costs and benefits can be quantified in the following chapter. The choice of these specific technologies offers greater data availability and environmental benefits while also providing practical, scalable, and economically relevant solutions for phosphorus recovery.

Finally, challenges of inconsistent data and the lack of standardization in existing studies were present in the phosphorus recovery technology assessment. Information on phosphorus recovery technologies is fragmented and inconsistent, making it hard to access and understand. Some articles focus on specific technologies while overlooking others, and descriptions vary across sources, especially in how technologies are classified (e.g., full-scale vs. pilot-scale). Terminology and recovery efficiency also lack standardization. Initiatives like ESPP provide extensive data, but a standardized database covering inputs, outputs, processes, efficiency, and costs would greatly help stakeholders in understanding this rapidly evolving field. Such a resource would improve understanding, reliability, and the dissemination of knowledge while addressing the uncertainties in current data.

5 Cost Benefit Analysis

This chapter presents the results for the firm-level and economic cost-benefit analysis for the identified phosphorus recovery technologies from municipal wastewater that had environmental benefits when compared to the business as usual practices in EU WWTP and that had recovered phosphorus products that could be readily used as fertilizer.

5.1 Firm Level CBA

The aim of this firm-level CBA analysis was to understand the effect of the selling price of struvite on the firm's profit. The costs and benefits data for the phosphorus recovery technologies were mainly taken from Egle et al. (2016). The study provides the cost of recovery for phosphorus considering a modification of a reference WWTP in central Europe, for 100k and 500k P.E. The costs in the study include investment and operational expenses. Investment costs are associated with acquiring the technology, reactors, and construction. Operational costs are divided into five categories: chemical resources, staff, energy, maintenance, and disposal. The benefits come from operational savings (better sludge dewatering, lower disposal costs, and reduced nutrient backflow) and the sale of recovered phosphorus products. The annual cost of each technology is given in euros/kg of recovered P and in euro/p.e./year, for two situations (1) without revenues and savings and (2) with revenues and savings. Importantly, Airprex and Pearl can be used in WWTPs of various sizes, while Leachphos and Recophos are only viable for larger plants (at least 1.75M p.e.) due to their need for high amounts of sludge ash.

According to the European Commission (2015), the base rates they provide are appropriate for use as financial discount rate (*Reference and discount rates—European Commission*, 2025). However, these base rates don't yet include the standard risk margin. Following the Commission's guidance, a 1% risk margin was added to each country's base rate. Since all cost and benefit values in the CBA were corrected for inflation to reflect 2024 prices, the discount rate was also based on 2024 data from the 27 EU member states. The average rate across countries and time was used as the project's discount rate (5.2%), with the lowest (3.8%) and highest (12.2%) values used for the sensitivity analysis. This data can be found in Appendix B.

For determining the time horizon of the CBA, two values were considered. The EU Commission (2015) suggests a time horizon of 30 years for CBAs of water infrastructure related projects, but they refer to bigger water and sanitation projects, such as building a new WWTP, or water distribution and sewage collection networks construction. Since the recovery technology project is smaller than these, the time horizon for the CBA was set to 15 years, based on the expected useful life of construction components (Egle et al., 2016).

More information on the methodology used and calculations done can be found in Appendix A (A1. Cost and Benefits of P Recovery Technologies from Wastewater) and B (the excel file with the calculations).

Figure 5, 6, 7 and 8 show the NPV for the Airprex, Pearl, Leachphos and Recophos, for the 1.75M p.e. WWTP, with a discount rate of 5.2%.

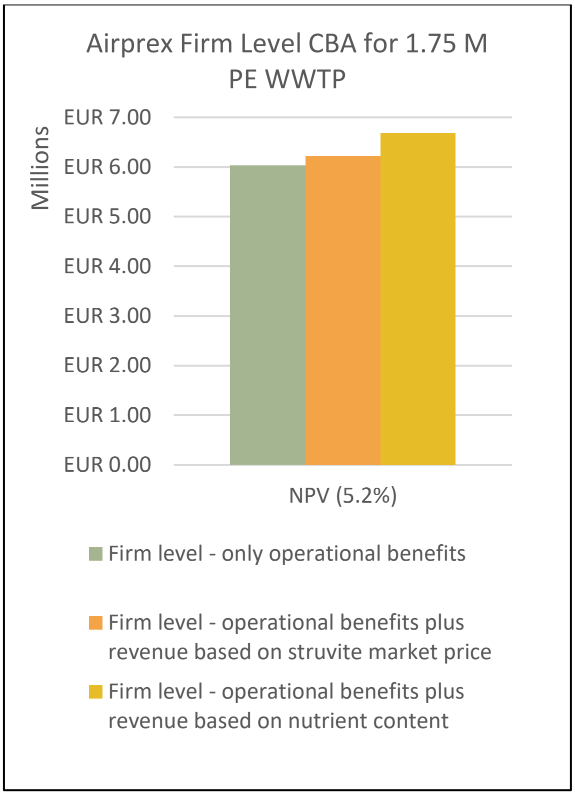

Figure 5. Firm-Level CBA Analysis for Airprex.

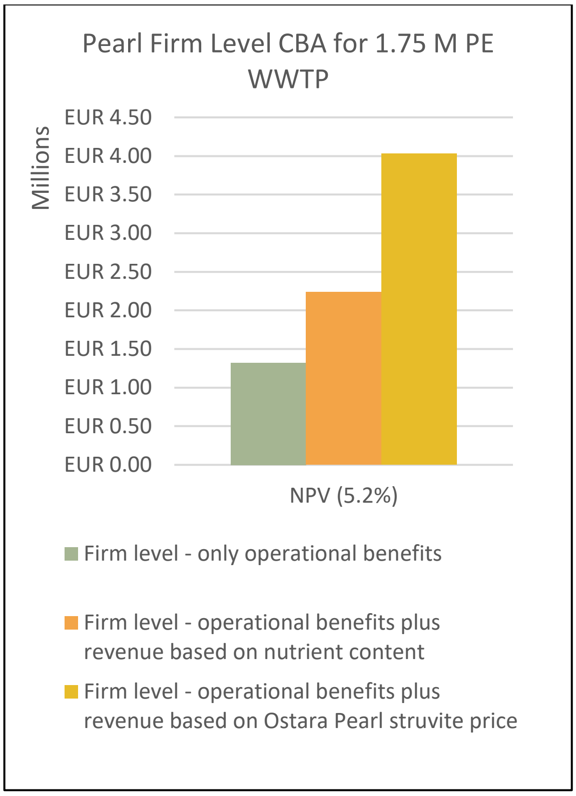

Figure 6. Firm-Level CBA Analysis for Pearl.

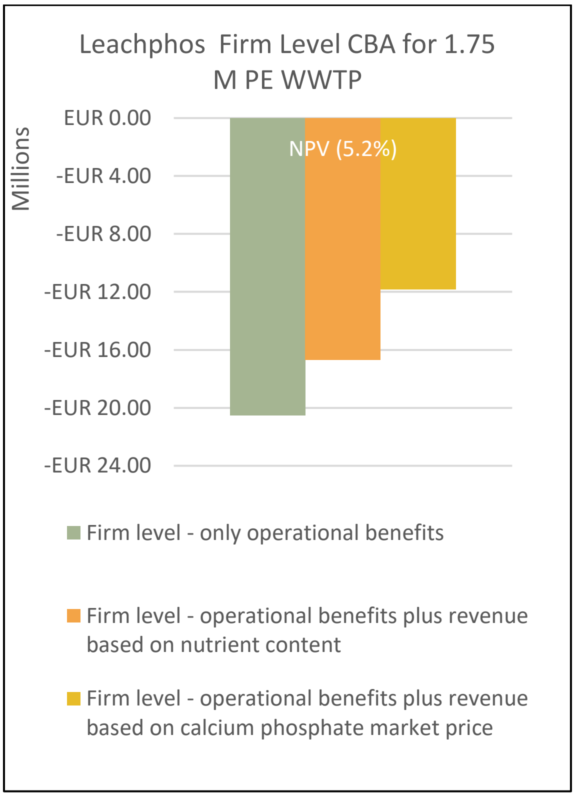

Figure 7. Firm-Level CBA Analysis for Leachphos.

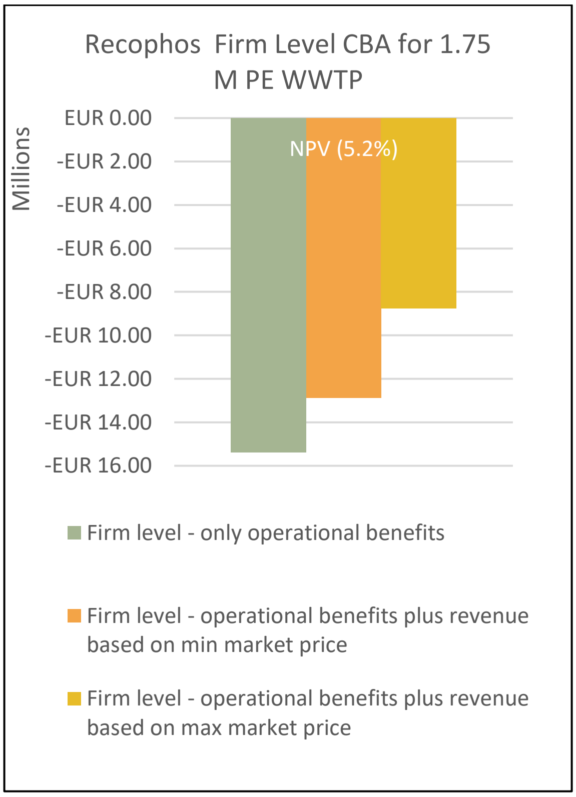

Figure 8. Firm-Level CBA Analysis for Recophos.

The presented results untangle the origin of the benefits, into operational and revenue from selling recovered products. As was already shown by Egle et al. (2016), both Airprex and Pearl are financially advantageous when all internal benefits are considered, with Airprex having higher net benefits than Pearl. The results show that the Airprex technology should be the chosen one to be implemented in an existing reference WWTP in the EU, with Pearl being the second choice because it presents a lower NPV than Airprex. The statement holds truth regardless of the struvite selling, adding further insights to the discussed study. While for Leachphos and Recophos, as was also previously shown by Egle et al. (2016), they don't present financial advantage at firm-level, even for higher selling prices of the recovered phosphorus product than what was considered in the previous study. However, these selling prices improve the negative NPV by approximately 20-42% and 16-42% for Leachphos and Recophos, respectively.

This drastic difference in NPV results between the group Airprex/Pearl and Leachphos/Recophos is firstly explained by the order of magnitude of the initial investment and the proportion of annual net operational benefits in comparison to the initial investments. Airprex and Pearl have cheaper initial investments (2.7M and 2.5M euros, respectively) than Leachphos and Recophos (25.4M and 9.5M euros, respectively). The operational benefits and costs for each technology are the same for every year with, respectively, the value of (1) 1.2M and 320K eur for Airprex, (2) 432K and 64K eur Pearl, (3) 4.5M eur and 4.1M eur for Leachphos and (4) 2.1M eur and 2.7M eur for Recophos. Therefore, for Recophos, the operational benefits are not enough to cover the operational costs, meaning that no profit is being made annually and thus it won't have a positive NPV under the analysed situation unless there is more revenue from the selling of the recovered product. Moreover, Airprex and Pearl have significantly more net operational benefits proportionally to the initial investments – 33%, 15.3%, 1.6% respectively for Airprex, Pearl, and Leachphos. Thus, for Leachphos the operational benefits are bigger than the operational costs, but they are just not sufficient to compensate for the initial investment.

5.1.1 Sensitivity Analysis

The firm-level sensitivity analysis was done for the discount rates of 3.8%, 5.2%, and 12.2% and for WWTP sizes 100k, 500k, 1M and 1.75M p.e.. Complete results can be found on the Appendix A (A4. Firm-Level CBA Results).

For Airprex, the NPV continues positive for all WWTP sizes and discount rates, again regardless of struvite selling but accounts for the operational benefits. While for Pearl, it is observed that the project doesn't always have a positive NPV. For the smaller WWTP (100k p.e.) all the NPVs are negative regardless of benefits and discount rates considered. For the WWTP of 500 p.e. and 1M p.e., the positivity of the NPV depends on the discount rate and on the selling of struvite and its selling price. While for the 1.75M p.e. WWTP, the NPV is always positive, regardless of selling of struvite and discount rates. For these three sizes of WWTP, the Airprex and Pearl technology have comparable NPVs when the Pearl technology has the revenue from Crystal Green. Though there is some uncertainty, it appears that Crystal Green, the Ostara Pearl trademarked struvite product, is valued in the market. Therefore, depending on the struvite market conditions and for medium to large sizes of WWTP, the conclusions are not certain regarding which of the two technologies to choose from. The results directly reflect one of the assumptions of the analysis: the economies of scale effect, that is bigger for Pearl than for Airprex. It also shows the importance of the discount rate when deciding whether to proceed or not with a project.

Whereas for Leachphos and Recophos the NPV continues negative and is in the same order of magnitude for the different discount rates. Given that they need a very large size of WWTP, no sensitivity analysis related to this factor was carried out, as 1.75M p.e is already one of the largest types of WWTP existent.

5.2 Societal CBA

The aim of the conducted economic CBA is understanding the effect of accounting for external benefits that are not accounted for in normal market valuation. This analysis included the environmental benefits calculated by a life-cycle assessment study (Amann et al., 2018) that had the same reference system and technologies as in Egle et al. (2016). This study analysed two categories of environmental impacts: global warming and acidification potential. The valuation of these environmental impacts was based on reference studies. More explanations can be found in Appendix A (considered environmental impacts and pricing of environmental impacts) and the calculations on Appendix B.

The considered discount rates were 3.5%, 4.5% and 5.5%. Boardman et al. (2018) recommend a social discount rate of 3.5% for intergenerational projects, those that do not have impacts after 50 years. This is the case considering that the expected useful lifetime of the acquired technologies is 15 years. Romijn and Renes (2013) affirm that it is usual to use social discount rate of 5.5%. Furthermore, a rate of 4.5% was selected as an intermediate value between these two reference points. The considered time horizon of the social CBA was the same one as for the firm-level CBA (15 years) because even though the social CBA aims to capture the effects of the project considering the environmental benefits that can be extended for many years, the construction parts still function under the same conditions, that is, the depreciation and useful operability of the machinery doesn't change if the goal is firm or social welfare.

Figure 9 shows the obtained results for this analysis. When considering the environmental benefits provided by the adoption of the considered technologies, all considered projects result in a net positive benefit for the discount rate of 4.5% and 1.75M p.e. size. The results for the social CBA differ greatly than for the firm-level. Now, all technologies present a positive NPV. With Recophos in first place, with 2.3B EUR NPV; followed by Pearl, with 1.0B EUR NPV, which is less than half the NPV of Recophos; then Airprex, with similar order of magnitude as Pearl but lower NPV of 0.9B EUR; and at last, Leachphos with significant lower NPV of 0.2B. Furthermore, Leachphos is in third place in the firm level CBA and in fourth in the social CBA. Therefore, when compared to the other technologies of this analysis, Leachphos shouldn't be the chosen phosphorus recovery technology.

This difference in results from firm-level to social CBA stems from the fact that the external benefits (monetized environmental benefits) of Recophos are significantly bigger than of its counterpart technologies.

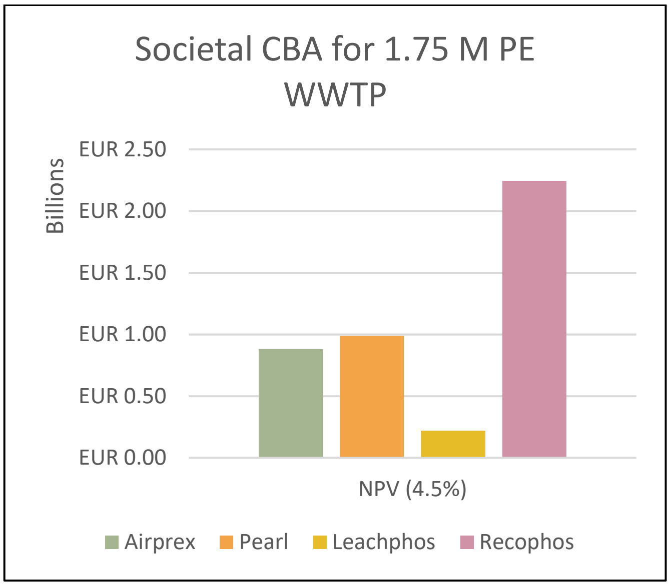

Figure 9. Societal CBA for 1.75M PE WWTP and discount rate of 4.5%.

5.2.1 Sensitivity Analysis

The sensitivity analysis for the societal CBA considers discount rates of 3.5%, 4.5%, and 5.5%, for minimum, mean and maximum monetization values of the environmental benefits, and for WWTP sizes of 100k, 500k, 1M and 1.75M p.e. (the WWTP size only for Airprex and Pearl). Complete results can be found on the Appendix A (A5. Societal CBA Results).

For Airprex and Pearl, the NPVs are within the same range for each WWTP size: 50M-75M EUR for 100K p.e., 230K-380K EUR for 500K p.e., 470K-770K EUR for 1M p.e., and 820K-1.3B EUR for 1.75M p.e., with Airprex having more NPVs (across different discount rates and valuation of environmental benefits) in the lower end of that range and Pearl more at the upper end. Given the uncertainty regarding the social discount rate and the monetization factors for environmental benefits, the sensitivity analysis reveals that actually these two technologies have comparable net social benefits.

As for the comparison of the four technologies in a 1.75M WWTP, the results stay almost the same regardless of the social discount rate and monetization values of the environmental benefits. Recophos is still the first choice, with the NPV ranging from 2.1B-3.1B EUR. Airprex and Pearl are actually comparable and draw in second place, as explained in the previous paragraph. Leachphos continues as the option with less net social benefits, with NPVs ranging from 200K-300K EUR.

6 Discussion and conclusions

6.1 Discussion

From the firm level and social CBA, the analysis showed that including environmental aspects can greatly change the results of which technology is preferred to be adopted. When externalities such as emissions that contribute to global warming and acidification potential are internalized through monetary valuation, technologies that may seem less economically attractive from a purely financial perspective can become more favorable overall. Even though firms are still most probable to choose the technologies that offer greater profit by accounting only costs and benefits that have market prices, following the firm level analysis of this study, these results are insightful for policy making. For example, the Recophos technology did not have viability at firm level, but it proved to have significant higher return when considering environmental benefits. In this case, the EU could provide economic incentives to facilitate the adoption of this technology, making its adoption more attractive to firms.

The EU should invest in identifying and encouraging the adoption of the most promising opportunities for phosphorus recovery. At the moment, the EU is promoting the recovery of phosphorus (general and specifically for WWTP) having set ambitious goals regardless of the technology being used. However, from the analysis, it can be seen that different recovery technologies provide more or less social welfare and are more or less financially attractive to companies. Since governments aim to improve social welfare, they could use insights from conducting studies like this one to define and incentivize certain phosphorus technologies that improve more the social welfare. Furthermore, instead of supporting many technologies, governments should prioritize advancing the most promising ones to have more full-scale examples that produce sufficient recovered phosphorus fertilizers, having more chance to compete with mineral fertilizers (Kabbe, 2019; Schipper, 2019; Pikaar et al., 2022).

It is also relevant to consider the importance of P recovery for EU's phosphorus, and therefore food, security. It has been estimated that the recovered P in the EU that displace the use of conventional fertilizers is 0.5%, with a maximum potential of 13% of all EU P fertilizer imports (Muys et al., 2021; Soo and Shon, 2024). Moreover, the soaring and unstable phosphorus commodities prices for 2020-2022 years, due to the pandemic, geopolitical and trade wars (Brownlie et al., 2023), negatively affected farmers and consumers (Chrispim et al., 2019). This raises an alert and makes it more relevant for the EU to actively aim for phosphorus self-sufficience and resillience to ensure its food security and population welfare.

The status of most phosphorus sustainability policies in the EU are command-and-control as reported in chapter 3, which comes with governance issues like enforcement deficits, rebound and shifting effects (Garkse and Ekardt, 2021). Furthermore, from what could be found, there aren't any current economic instruments on EU level that foster phosphorus circular economy. However, this type of instrument is essential to advance phosphorus recovery technologies in WWTP (Soo and Shon, 2024). Furthermore, it has been shown that economic instruments have advantages when compared to command-and-control ones, with a mix of these two types being needed for effective phosphorus management (Garske et al., 2025; Stubenrauch, 2022). Tying the phosphorus agenda with other environment related issues, such as climate and biodiversity, has been pointed out as a promising path to achieve more sustainability regarding the use and disposal of this nutrient (Garske and Ekardt, 2021; Haygarth and Mezeli, 2023).

6.2 Limitations

While this research provides insights, it is important to consider its limitations when interpreting the findings.

A key limitation encountered in this research is the limited availability and clarity of information on phosphorus recovery technologies. First, much of the existing data is difficult to find or interpret due to the large number of technologies and lack of standardization in how these technologies are described. The absence of a standardized way to present phosphorus recovery technologies further complicates the understanding and dissemination of knowledge, adding to the uncertainty and reducing the reliability of the available data. Second, there is a small amount of publicly available data especially on the cost of these technologies. Up to this date, research in the field still uses cost values from Egle et al. (2016), due to lack of most recent studies. Third, the rapid pace of technological innovation in this field means that available data (from academic research) doesn't represent what is being used in the industry, further contributing to uncertainty. While initiatives such as the ESPP offer valuable information, a centralized, standardized and up-to-date database (with information on input and output materials, process types, efficiency, costs, and other relevant parameters) would greatly improve transparency and reliability. This would also support stakeholder understanding, especially for those that are not specialists, and thus support more informed decision-making.

In addition, despite the chapter on EU policies and legislation being developed consulting key references, it is important to state that some regulations might not have been included or updated during the execution of the thesis.

Even though in general, and in comparison with the rest of the world, EU sewage treatment is quite established and advanced, there are notable differences between EU countries. Due to difficulty of finding specific data, these differences had to be put aside. Therefore, the results might vary significantly on the specific EU country considered.

Furthermore, a choice was made to analyze four out of the more than twenty possible technologies for phosphorus recovery technologies from wastewater, due to scope and time constraints. Moreover, this choice was partially based on the technologies having positive environmental benefits, data based on a secondary source (Amann et al., 2018). Though this study is insightful, it didn't include all relevant environmental impact categories and the boundaries didn't include the agricultural application and spread of the fertilizer. The selection of the reference system can also affect the results. In this study, the comparison was between a business-as-usual WWTP and an adapted one that recovered phosphorus. However, the comparison between the production of mineral phosphorus fertilizers and recovered phosphorus fertilizers is also relevant.

The valuation of environmental aspects is also a controversial subject, as it involves significant uncertainty. Therefore, even though the chosen monetization factors are taken from reliable sources, they are estimations subject to variation and may not fully capture the complexity of environmental impacts.

Finally, the social CBA didn't include social aspects of phosphorus recovery and recycling.

6.3 Conclusions

Phosphorus is a key aspect in sustainability and circular economy. However, it lacks a global intergovernmental agreement, although it is a recognized issue since 2011. In the EU, phosphorus management is crucial due to its essential role in food security, environmental sustainability, and reducing dependence on external phosphorus sources. The EU has shown global leadership in phosphorus management through a broad package of regulations, directives, and policies, such as the Sewage Sludge Directive, Urban Wastewater Directive, and the European Green Deal, the EU Fertilizing Products Regulation and Circular Economy Action Plan. However, there are still significant challenges due to fragmented policies, governance gaps, and insufficient economic incentives to incentivize the shift to a more circular economy, specifically in respect to phosphorus.

Furthermore, this research analyzed the recovery potential of phosphorus from various waste streams, identifying that in the EU sewage wastewater is the most promising one to recover phosphorus because of its high P content and existence of advanced and established recovery technologies. The most promising phosphorus recovery technologies for domestic wastewater - considering large scale applications, environmental benefits and recovered products readily usable as fertilizer - are Airprex, Pearl, Leachphos and Recophos. The firm level CBA showed that Airprex consistently has positive NPVs, while Pearl's NPV depends on WWTP size, discount rate and struvite selling price. It also showed that for the considered discount rates and recovered phosphorus material pricing, Leachphos and Recophos don't achieve positive NPV. The social CBA revealed that considering the monetization of environmental impacts of the technologies drastically changes the NPV results, and which is the better alternative. The NPVs for all technologies are positive, with Recophos being the first choice, followed by Airprex in a draw with Pearl. At last is Leachphos, which performs poorly when compared to the other technologies.

For policy-makers, the results present insights on how to best promote phosphorus recovery in the EU. This research highlights the importance of incorporating environmental externalities into phosphorus recovery governmental decision-making, showing that less profitable technologies in economic terms can become more feasible when broader societal impacts are included. To achieve this, economic instruments, such as subsidies or taxes, can complement existing command-and-control policy, leading to more effective and widespread phosphorus recovery practices.

6.4 Recommendation for further research

Though domestic wastewater was identified as the most promosing waste stream to recover phosphorus, studying other waste stream alternatives that also have high amount of P in the EU, such as manure, and food waste, is important to realize the goals of EU's phosphorus agenda.

Further studies that focus on wastewater should include all available phosphorus recovery technologies and the direct recycling of sewage sludge (direct agricultural application), prioritizing the ones that are operational at full scale, and a thorough life cycle assessment analysis (or other environmental impact assessment methodology) should be conducted. Ideally, all relevant categories should be included in the study. The selected analyzed technologies had environmental benefits but only when considering two categories (global warming potential and acidification potential) because this was limited to the data that could be found from other studies. Therefore, it is important to consider other impact categories such as human toxicity (important due to the presence of heavy metals in phosphorus fertilizers and contaminants of emerging concern such as pharmaceuticals) and freshwater and marine eutrophication. The reference systems should not only be a WWTP but also mineral fertilizer production. The boundary of the system should also include the agricultural application of the fertilizer and further decomposition and spreading through the environment.

Numerical analysis of the application of economic instruments, such as subsidies and taxes, in the EU in the context of adoption of phosphorus recovery technologies would provide more insights into how these instruments can aid in sustainable resource management.

References

Achilleos, P., Roberts, K. R., & Williams, I. D. (2022). Struvite precipitation within wastewater treatment: A problem or a circular economy opportunity? *Heliyon*, *8*(7). https://doi.org/10.1016/j.heliyon.2022.e09862

Akinnawo, S. O. (2023). Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. In *Environmental Challenges* (Vol. 12). Elsevier B.V. https://doi.org/10.1016/j.envc.2023.100733

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., & Egle, L. (2018). Environmental impacts of phosphorus recovery from municipal wastewater. *Resources, Conservation and Recycling*, *130*, 127–139. https://doi.org/10.1016/j.resconrec.2017.11.002

Ashley, K., Cordell, D., & Mavinic, D. (2011). A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse. *Chemosphere*, *84*(6), 737–746. https://doi.org/10.1016/j.chemosphere.2011.03.001

Bigalke, M., A. Ulrich, A. Rehmus, and A. Keller. (2017). Accumulation of cadmium and uranium in arable soils in Switzerland. Environ. Pollut. 221: 85–93. https://doi.org/10.1016/j.envpol.2016.11.035

Boardman, A.E., Greenberg, D.H., Vining, A.R., and Weimer, D.L. (2018). Cost-Benefit Analysis: Concepts and Practice. Fifth Edition. Cambridge University Press, Cambridge, UK.

de Boer, M. A., Romeo-Hall, A. G., Rooimans, T. M., & Slootweg, J. C. (2018). An assessment of the drivers and barriers for the deployment of urban phosphorus recovery technologies: A case study of the Netherlands. *Sustainability (Switzerland)*, *10*(6). https://doi.org/10.3390/su10061790

de Boer, M. A., Wolzak, L., & Slootweg, J. C. (2019). Chapter 5. Phosphorus: Reserves, production, and applications. In *Phosphorus Recovery and Recycling* (pp. 75–100). Springer Singapore. https://doi.org/10.1007/978-981-10-8031-9_5

Brownlie, W. J., Sutton, M. A., de Boer, M. A., Camprubí, L., Hamilton, H. A., Heal, K. v, Morgandi, T., Neset, T.-S., & Spears, B. M. (2021). Chapter 2. Phosphorus reserves, resources and uses. In *Our Phosphorus Future*. https://doi.org/10.13140/RG.2.2.25016.83209

Brownlie, W. J., Sakrabani, R., Metson, G. S., Blackwell, M. S. A., & Spears, B. M. (2022a). Chapter 6. Opportunities to recycle phosphorus-rich organic materials. In *Our Phosphorus Future*. https://doi.org/10.13140/RG.2.2.33143.29605

Brownlie, W. J., Spears, B. M., Heal, K. v, Reay, D. S., Sutton, M. A., Benton, T. G., Cordell, D., Heathwaite, A. L., Hermann, L., Johnes, P. J., Masso, C., Mcdowell, R. W., Mcgrath, J. W., Metson, G. S., Sakrabani, R., Vanderbeck, I., & Zhang, F. (2022b). Chapter 9. Towards our phosphorus future. In *Our Phosphorus Future*. https://doi.org/10.13140/RG.2.2.16995.22561

Brownlie, W. J., Sutton, M. A., Cordell, D., Reay, D. S., Heal, K. v, Withers, P. J. A., Vanderbeck, I., & Spears, B. M. (2023). *Phosphorus price spikes: A wake-up call for phosphorus resilience*. https://doi.org/https://doi.org/10.3389/fsufs.2023.1088776

Brownlie, W. J., Alexander, P., Cordell, D., Maslin, M., Metson, G. S., Sutton, M. A., & Spears, B. M. (2024). National phosphorus planning for food and environmental security. In *Current Opinion in Biotechnology* (Vol. 90). Elsevier Ltd. https://doi.org/10.1016/j.copbio.2024.103226

de Bruyn, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., Vergeer, R., & Ahdour, S. (2018). *Environmental Prices Handbook EU28 versionN54-Environmental Prices Handbook Environmental Prices Handbook EU28 version*.

Canziani, R., Boniardi, G., & Turolla, A. (2023). Phosphorus recovery—recent developments and case studies. In *Sustainable and Circular Management of Resources and Waste Towards a Green Deal* (pp. 269–281). Elsevier. https://doi.org/10.1016/B978-0-323-95278-1.00007-3

Carrillo, V., Castillo, R., Magrí, A., Holzapfel, E., & Vidal, G. (2024). Phosphorus recovery from domestic wastewater: A review of the institutional framework. *Journal of Environmental Management*, *351*. https://doi.org/10.1016/j.jenvman.2023.119812

CAP 2023-27 - European Commission. ([n.d.]). Retrieved on 17 November, 2024, from https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-2023-27_en

Case, S.D.C., M. Oelofse, Y. Hou, O. Oenema, and L.S. Jensen. (2017). Farmer perceptions and use of organic waste products as fertilisers – A survey study of potential benefits and barriers. Agric. Syst. 151: 84–95. https://doi.org/10.1016/j.agsy.2016.11.012

Circular economy action plan—European Commission. ([n.d.]). Retrieved 11 April 2025, from https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

Chrispim, M. C., Scholz, M., & Nolasco, M. A. (2019). Phosphorus recovery from municipal wastewater treatment: Critical review of challenges and opportunities for developing countries. In *Journal of Environmental Management* (Vol. 248). Academic Press. https://doi.org/10.1016/j.jenvman.2019.109268

Comber, S., Gardner, M., Georges, K., Blackwood, D., & Gilmour, D. (2013). Domestic source of phosphorus to sewage treatment works. *Environmental Technology*, *34*(10), 1349–1358. https://doi.org/10.1080/09593330.2012.747003

Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, *19*(2), 292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009

Cordell, D., Rosemarin, A., Schröder, J. J., & Smit, A. L. (2011). Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. *Chemosphere*, *84*(6), 747–758. https://doi.org/10.1016/j.chemosphere.2011.02.032

Cordell, D., & White, S. (2011). Peak phosphorus: Clarifying the key issues of a vigorous debate about long-term phosphorus security. *Sustainability*, *3*(10), 2027–2049. https://doi.org/10.3390/su3102027

Cordell, D., and S. White. (2015). Phosphorus security: global non-governance of a critical resource for food security. In: Pattberg, P. And Fariborz Zelli, F., editors, Encyclopedia of Global Environmental Politics and Governance.

Cornel, P., & Schaum, C. (2009). Phosphorus recovery from wastewater needs an integrated approach. *Water Science and Technology,* *59*(6), 1069–1076. https://doi.org/10.2166/wst.2009.045

Council of the European Union. (1986). Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31986L0278

Council of the European Union. (2024). *An EU critical raw materials act for the future of EU supply chains*. Retrieved November 6, 2024, from https://www.consilium.europa.eu/en/infographics/critical-raw-materials/

De Ridder, M., de Jong, S., Polchar, J., Lingeman, S. (2012). Risks and Opportunities in the Global Phosphate Rock Market. The Hague Centre for Strategic Studies, The Hague.

van Dijk, K. C., Lesschen, J. P., & Oenema, O. (2016). Phosphorus flows and balances of the European Union Member States. *Science of The Total Environment*, *542*, 1078–1093. https://doi.org/10.1016/J.SCITOTENV.2015.08.048

Drinan, J. E., & Spellman, F. R. (2013). *Water and wastewater treatment: A guide for the nonengineering professional* (2nd ed.). CRC Press.

Eco-schemes—European commission. (2024). Retrived 13 November from https://agriculture.ec.europa.eu/common-agricultural-policy/income-support/eco-schemes_en

Egle, L., Rechberger, H., Krampe, J., & Zessner, M. (2016). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Science of the Total Environment*, *571*, 522–542. https://doi.org/10.1016/j.scitotenv.2016.07.019

Ensuring availability and affordability of fertilizers—European Commission. ([n.d]). https://agriculture.ec.europa.eu/common-agricultural-policy/agri-food-supply-chain/ensuring-availability-and-affordability-fertilisers_en

European Central Bank. (2024). Harmonised index of consumer prices (HICP) [Data set]. https://data.ecb.europa.eu/data/datasets/ICP/ICP.M.U2.N.000000.4.INX

European Commission. ([n.d.]). Energy, Climate change, Environment. Circular economy action plan. Retrieved November 11, 2024, from https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

European Commission - Nutrients action plan for better management. ([n.d.]). Retrieved 18 November, 2024, from https://ec.europa.eu/info/law/better-regulation/

European Commission. (2014). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: On the review of the list of critical raw materials for the EU and the implementation of the raw materials initiative (COM(2014) 297 final). EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0297

European Commission. (2015). *Guide to Cost-Benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014-2020*. Luxembourg: Publications Office of the European Union. ISBN 978-92-79-34796-2. doi:10.2776/97516. Available at: https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf

European Commission. (2017). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 list of critical raw materials for the EU (COM(2017) 490 final). EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0490

European Environment Agency. (2020). *Urban wastewater treatment in Europe*. European Union. Retrieved January 28, 2025, from https://water.europa.eu/freshwater/countries/uwwt/european-union

European Parliament. (2024). Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020. EUR-Lex. http://data.europa.eu/eli/reg/2024/1252/2024-05-03/eng

European Parliament and Council (EPC). (2018). Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste (Text with EEA relevance). EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32018L0850

European Parliament and Council (EPC). (2019). Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1009

European Parliament and Council (EPC). (2021). Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R2115

European Parliament and Council (EPC). (2024). *Directive Of The European Parliament And Of The Council Concerning Urban Wastewater Treatment (Recast)*. https://data.consilium.europa.eu/doc/document/PE-85-2024-REV-1/en/pdf

European Sustainable Phosphorus Platform. (2025). *P-recovery technology inventory*. Retrieved January 10, 2025, from https://www.phosphorusplatform.eu/activities/p-recovery-technology-inventory

European Sustainable Phosphorus Platform. (2021). *Catalogue for Nutrient Recovery Technologies*. Retrieved January 14, 2025, from http://www.phosphorusplatform.eu/p-recovery-technology-inventory.

European Sustainable Phosphorus Platform. (2023). *Why should elemental phosphorus (P4) and purified phosphoric acid (PPA) both be on the EU list of "Strategic Raw Materials"?* https://www.phosphorusplatform.eu/images/Regulatory%20activities/Declaration%20P4%20PPA%20SRMs%20v17-7_23.pdf

European Sustainable Phosphorus Platform. (2024). *ESPP eNews No. 87*. European Sustainable Phosphorus Platform. https://www.phosphorusplatform.eu/scope-in-print/enews/2546-espp-enews-no-87-june-2024

Farm to fork strategy—European commission. ([n.d.]). Retrieved 13 November 2024, from https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en

Fattah, K. P. (2012). Assessing Struvite Formation Potential at Wastewater Treatment Plants. *International Journal of Environmental Science and Development*, 548–552. https://doi.org/10.7763/ijesd.2012.v3.284

Fertilising products—European commission. ([n.d.]). Retrieved 11 November 2024, from https://single-market-economy.ec.europa.eu/sectors/chemicals/fertilising-products_en

Grizzetti, B., Vigiak, O., Aguilera, E., Aloe, A., Biganzoli, F., Billen, G., Caldeira, C., De, M. A., Egle, L., Einarsson, R., Garnier, J., Gingrich, S., Hristov, J., Huygens, D., Koeble, R., Lassaletta, L., Le, N. J., Liakos, L., Lugato, E., ... Zanni, M. (2023). *Knowledge for integrated nutrient management action plan (INMAP)*. JRC Publications Repository. https://doi.org/10.2760/692320

Garske, B., & Ekardt, F. (2021). Economic policy instruments for sustainable phosphorus management: taking into account climate and biodiversity targets. *Environmental Sciences Europe*, *33*(1). https://doi.org/10.1186/s12302-021-00499-7

Garske, B., Heyl, K., & Ekardt, F. (2025). How economic instruments address sustainable nutrient use: the example of phosphorus governance. *Environmental Sciences Europe*, *37*(1). https://doi.org/10.1186/s12302-024-01045-x

Ghosh, S., Lobanov, S., & Lo, V. K. (2019). An overview of technologies to recover phosphorus as struvite from wastewater: advantages and shortcomings. In *Environmental Science and Pollution Research* (Vol. 26, Issue 19, pp. 19063–19077). Springer Verlag. https://doi.org/10.1007/s11356-019-05378-6

Haygarth, P. M., & Mezeli, M. M. (2023). Opportunity to improve global phosphorus governance. *Nature Food*, *4*(10), 837–838. https://doi.org/10.1038/s43016-023-00860-4

Hermann, L., & Hermann, R. (2022). Chapter 13. Resource recovery from used water: The (European) regulator's point of view. In *Resource Recovery from Water*. IWA Publishing. https://doi.org/10.2166/9781780409566

Hermann, L., Mcgrath, J. W., Kabbe, C., Macintosh, K. A., van Dijk, K., & Brownlie, W. J. (2022). Chapter 7. Opportunities for recovering phosphorus from residue streams. In Our Phosphorus Future. https://doi.org/10.13140/RG.2.2.16366.08006

Huber, M., Athanasiadis, K., & Helmreich, B. (2020). Phosphorus removal potential at sewage treatment plants in Bavaria – a case study. *Environmental Challenges*, *1*. https://doi.org/10.1016/j.envc.2020.100008

Hukari, S., Hermann, L., & Nättorp, A. (2016). From wastewater to fertilisers - Technical overview and critical review of European legislation governing phosphorus recycling. *Science of the Total Environment*, *542*, 1127–1135. https://doi.org/10.1016/j.scitotenv.2015.09.064

Jupp, A.R., Beijer, S., Narain, G.C., Schipper, W., Slootweg, J.C., 2021. Phosphorus recovery and recycling–closing the loop. Chem. Soc. Rev. 50, 87–101. https://doi.org/10.1039/D0CS01150A.

Kabbe, C. (2019). *Global Compendium on Phosphorus Recovery from Sewage/Sludge/Ash*.

Kabbe, C. (2023). *P-recovery technology implementation table*. European Sustainable Phosphorus Platform. Retrieved January 10, 2025, from https://www.phosphorusplatform.eu/activities/p-recovery-technology-inventory#recovery-p

Kalpakchiev, T., Fraundorfer, M., Jacobs, B., Martin-Ortega, J., & Cordell, D. (2023). Transforming the European Union's phosphorus governance through holistic and intersectoral framings. *Frontiers in Sustainable Resource Management*, *2*. https://doi.org/10.3389/fsrma.2023.1273271

Kanter, D.R., and W.J. Brownlie. 2019. Joint nitrogen and phosphorus management for sustainable development and climate goals. Environ.Sci. Policy 92: 1–8. https://doi.org/doi:10.1016/J.ENVSCI.2018.10.020

van Kauwenbergh, S. J., Stewart, M., & Mikkelsen, R. (2013). World Reserves of Phosphate Rock... a Dynamic and Unfolding Story. *Better Crops*, *97*.

Kleinman, P. J. A., Sharpley, A. N., Withers, P. J. A., Bergström, L., Johnson, L. T., & Doody, D. G. (2015). Implementing agricultural phosphorus science and management to combat eutrophication. *Ambio*, *44*(2), 297–310. https://doi.org/10.1007/s13280-015-0631-2

Law, K. P., & Pagilla, K. R. (2018). Phosphorus recovery by methods beyond struvite precipitation. *Water Environment Research*, *90*(9), 840–850. https://doi.org/10.2175/106143017X15131012188006

Martin-Hernandez, E., Omelon, S., Vaneeckhaute, C., & Ruiz-Mercado, G. J. (2024). Phosphorus Recovery in Municipal Wastewater and Socioeconomic Impacts in Canada and the United States. *ACS ES and T Water*. https://doi.org/10.1021/acsestwater.4c00569

Masso, C., Zhang, F., Adhya, T. K., Blackwell, M. S. A., Macintosh, K. A., Johnes, P. J., Haygarth, P. M., Withers, P. J. A., Feng, G., Li, H., Zhang, C., Wu, J., Shen, J., Stutter, M. I., Cheng, L., & Brownlie, W. J. (2022). Chapter 4. Opportunities for better phosphorus use in agriculture. In *Our Phosphorus Future*. https://doi.org/10.13140/RG.2.2.31727.71846

Matsubae, K., Webeck, E. (2019). Phosphorus Flows in Asia. In: Ohtake, H., Tsuneda, S. (eds) Phosphorus Recovery and Recycling. Springer, Singapore. https://doi.org/10.1007/978-981-10-8031-9_2

Mayer, B. K., Baker, L. A., Boyer, T. H., Drechsel, P., Gifford, M., Hanjra, M. A., Parameswaran, P., Stoltzfus, J., Westerhoff, P., & Rittmann, B. E. (2016). Total value of phosphorus recovery. *Environmental Science & Technology*, *50*(13), 6606–6620. https://doi.org/10.1021/acs.est.6b01239

Metcalf & Eddy. (2013). *Wastewater engineering: Treatment and resource recovery* (5th ed.). McGraw-Hill Education.

Minnesota Pollution Control Agency. (2006). *Phosphorus: Sources, forms, impact on water quality – A general overview*. https://www.pca.state.mn.us/sites/default/files/wq-wwtp9-02.pdf

Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., & Garrido-Baserba, M. (2011). Economic feasibility study for phosphorus recovery processes. *Ambio*, *40*(4), 408–416. https://doi.org/10.1007/s13280-010-0101-9

Muys, M., Phukan, R., Brader, G., Samad, A., Moretti, M., Haiden, B., Pluchon, S., Roest, K., Vlaeminck, S. E., & Spiller, M. (2021). A systematic comparison of commercially produced struvite: Quantities, qualities and soil-maize phosphorus availability. *Science of the Total Environment*, *756*. https://doi.org/10.1016/j.scitotenv.2020.143726

Ohtake, H., & Tsuneda, S. (2018). Phosphorus Recovery and Recycling. In *Phosphorus Recovery and Recycling*. Springer Singapore. https://doi.org/10.1007/978-981-10-8031-9

Patyal, V., Jaspal, D., & Khare, K. (2023). Insight into technologies for phosphorus recovery from municipal wastewater treatment plants. In *Resource Recovery in Municipal Waste Waters* (pp. 107–126). Elsevier. https://doi.org/10.1016/B978-0-323-99348-7.00008-4

Penuelas, J., Coello, F., & Sardans, J. (2023). A better use of fertilizers is needed for global food security and environmental sustainability. In *Agriculture and Food Security* (Vol. 12, Issue 1). BioMed Central Ltd. https://doi.org/10.1186/s40066-023-00409-5

Pikaar, Ilje., Guest, Jeremy., Ganigué, Ramon., Jensen, Paul., Rabaey, Korneel., Seviour, Thomas., Trimmer, John., Kolk, O. van der., Vaneeckhaute, Céline., & Verstraete, Willy. (2022). *Resource recovery from water principles and application*. IWA Publishing.

Questions and Answers: Farm to Fork Strategy - building a healthy and fully sustainable food system. ([n.d.]). [Text]. European Commission - European Commission. Retrieved 13 November 2024, from https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_885

Questions and answers on the European critical raw materials act. (2023). European Commission. Retrieved November 7, 2024, from https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_1662

Questions and Answers on the new EU rules on treating urban wastewater. ([n.d.]). European Commission. Retrieved 17 November 2024, from https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_6281

Rashid, S. S., Liu, Y. Q., & Zhang, C. (2020). Upgrading a large and centralised municipal wastewater treatment plant with sequencing batch reactor technology for integrated nutrient removal and phosphorus recovery: Environmental and economic life cycle performance. *Science of the Total Environment*, *749*. https://doi.org/10.1016/j.scitotenv.2020.141465

Reference and discount rates—European Commission. (2025). Retrieved 7 April 2025, from https://competition-policy.ec.europa.eu/document/download/846ab160-b622-4771-98fe-b751c0b48949_en?filename=reference_rates_base_rates2025_04_croatia_eurozone.pdf

Reta, G., Dong, X., Li, Z., Su, B., Hu, X., Bo, H., Yu, D., Wan, H., Liu, J., Li, Y., Xu, G., Wang, K., & Xu, S. (2018). Environmental impact of phosphate mining and beneficiation: Review. *International Journal of Hydrology*, *2*(4). https://doi.org/10.15406/ijh.2018.02.00106

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., ... Walker, B. (2009a). *Planetary*

Boundaries: Exploring the Safe Operating Space for Humanity (Vol. 14, Issue 2). http://www.ecologyandsociety.org/vol14/iss2/art32/

Rockström, J., Steffen, W., & Noone, K. (2009b). A safe operating space for humanity. *Nature*, *461*, 472–475. https://doi.org/10.1038/461472a

Romijn, G., Renes, G. (2013). General Guidance for Cost-Benefit Analysis. CPB/PBL, The Hague. https://www.pbl.nl/en/publications/general-guidance-for-cost-benefit-analysis

Rout, P. R., Shahid, M. K., Dash, R. R., Bhunia, P., Liu, D., Varjani, S., Zhang, T. C., & Surampalli, R. Y. (2021). Nutrient removal from domestic wastewater: A comprehensive review on conventional and advanced technologies. *Journal of Environmental Management*, *296*. https://doi.org/10.1016/j.jenvman.2021.113246

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., ... Rockström, J. (2023). *Earth beyond six of nine planetary boundaries*. h http://doi.org/10.1126/sciadv.adh2458

Salkunić, A., Vuković, J., & Smiljanić, S. (2022). Review of Technologies for the Recovery of Phosphorus from Waste Streams. In *Chemical and Biochemical Engineering Quarterly* (Vol. 36, Issue 2, pp. 91–116). Assoc. of Chemists and Chemical Engineers of Croatia. https://doi.org/10.15255/CABEQ.2022.2066

Sánchez, A. S. (2020). Technical and economic feasibility of phosphorus recovery from wastewater in São Paulo's Metropolitan Region. *Journal of Water Process Engineering*, *38*. https://doi.org/10.1016/j.jwpe.2020.101537

Sandström, V., Kaseva, J., Porkka, M., Kuisma, M., Sakieh, Y., & Kahiluoto, H. (2023). Disparate history of transgressing planetary boundaries for nutrients. *Global Environmental Change*, *78*. https://doi.org/10.1016/j.gloenvcha.2022.102628

Schaum, C., Withers, P.J., Bowes, M. J., Farmer, A. M., et al. (2020). *Phosphorus: Polluter and resource of the future*. IWA Publishing. https://doi.org/10.2166/9781780408361

Schipper, W. (2019). Chapter 6. Success Factors for Implementing Phosphorus Recycling Technologies. In: Ohtake, H. and Tsuneda, S., editors, Phosphorus Recovery and Recycling. Springer, Singapore. p. 101–130. https://doi.org/10.1007/978-981-10-8031-9_6

Spears, B. M., Sutton, M. A., Heal, K. v, Reay, D. S., & Brownlie, W. J. (2022). Chapter 1. Our Phosphorus Future - an introduction. In *Our Phosphorus Future*. https://doi.org/10.13140/RG.2.2.32933.58085

Sewage sludge—European commission. (2024). Retrieved on 13 November 2024, from https://environment.ec.europa.eu/topics/waste-and-recycling/sewage-sludge_en

Soo, A., & Shon, H. K. (2024). A nutrient circular economy framework for wastewater treatment plants. *Desalination*, *592*. https://doi.org/10.1016/j.desal.2024.118090

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223). https://doi.org/10.1126/science.1259855

Stubenrauch, J. (2022). Innovative Phosphorus Governance: How to Address Recurring Regulatory Shortfalls—The Example of Germany, Costa Rica and Nicaragua. In: Ginzky, H., *et al*. International Yearbook of Soil Law and Policy 2020/2021. International Yearbook of Soil Law and Policy, vol 2020. Springer, Cham. https://doi.org/10.1007/978-3-030-96347-7_17

Syers, K., M. Bekunda, D. Cordell, J. Corman, J. Johnston, et al. (2011). Phosphorus and food production. UNEP Year Book 2011. Emerging issues in our global environment. United Nations Environment Programme, Nairobi. pp. 34–45. Retrieved 22 January 2025, from https://fsc.uni-hohenheim.de/fileadmin/einrichtungen/fsc/Intranet/Intranet_MOSA/MOSA_Updated/5_UNEP_2011.pdf

The European Green Deal—European Commission. (n.d). Retrieved 13 November, from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

The Helsinki Declaration. (2019). The OPF Report. Retrieved 18 November 2024, from https://www.opfglobal.com/helsinki-declaration

Towler, G., & Sinnott, R. (2012). *Chemical engineering design: Principles, practice and economics of plant and process design*. Elsevier.

Types of legislation - EU. ([n.d.]). Retrieved on 16 November 2024, from https://european-union.europa.eu/institutions-law-budget/law/types-legislation_en

Ulrich, A. E. (2019). Cadmium governance in Europe's phosphate fertilizers: Not so fast? In *Science of the Total Environment* (Vol. 650, pp. 541–545). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2018.09.014

Urban wastewater — European commission. ([n.d.]). Retrieved on 14 November 2024, from https://environment.ec.europa.eu/topics/water/urban-wastewater_en

U.S. Geological Survey. (2024). *Mineral Commodities Summaries 2024: U.S. Geological Survey*.

de Vries, W., Kros, J., Kroeze, C., & Seitzinger, S. P. (2013). Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. In *Current Opinion in Environmental Sustainability* (Vol. 5, Issues 3–4, pp. 392–402). https://doi.org/10.1016/j.cosust.2013.07.004

van Vuuren, D. P., Bouwman, A. F., & Beusen, A. H. W. (2010). Phosphorus demand for the 1970–2100 period: A scenario analysis of resource depletion. *Global Environmental Change*, *20*(3), 428–439. https://doi.org/10.1016/j.gloenvcha.2010.04.004

Walsh, M., Schenk, G., & Schmidt, S. (2023). Realising the circular phosphorus economy delivers for sustainable development goals. *Npj Sustainable Agriculture*, *1*(1). https://doi.org/10.1038/s44264-023-00002-0

Wassen, M. J., Schrader, J., Eppinga, M. B., Sardans, J., Berendse, F., Beunen, R., Peñuelas, J., & van Dijk, J. (2022). The EU needs a nutrient directive. In *Nature Reviews Earth and Environment* (Vol. 3, Issue 5, pp. 287–288). Springer Nature. https://doi.org/10.1038/s43017-022-00295-8

Waste framework directive—European commission. ([n.d.]). Retrieved 18 November 2024, from https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

Weikard, H. P. (2016). Phosphorus recycling and food security in the long run: a conceptual modelling approach. *Food Security*, *8*(2), 405–414. https://doi.org/10.1007/s12571-016-0551-4

Wilfert, P., Suresh Kumar, P., Korving, L., Witkamp, G.-J., & van Loosdrecht, M. C. M. (2015). The relevance of phosphorus and iron chemistry to the recovery of phosphorus from wastewater: A review. *Environmental Science & Technology, 49*(16), 9400–9414. https://doi.org/10.1021/acs.est.5b00150

Wiśniowska, E. (2023). Regional strategies for the management of phosphorus. In *Sustainable and Circular Management of Resources and Waste Towards a Green Deal* (pp. 225–233). Elsevier. https://doi.org/10.1016/B978-0-323-95278-1.00020-6

Witek-Krowiak, A., Gorazda, K., Szopa, D., Trzaska, K., Moustakas, K., & Chojnacka, K. (2022). Phosphorus recovery from wastewater and bio-based waste: an overview. In *Bioengineered* (Vol. 13, Issue 5, pp. 13474–13506). Taylor and Francis Ltd. https://doi.org/10.1080/21655979.2022.2077894

White, N. (2015). Conflict Stalemate in Morocco and Western Sahara: Natural Resources, Legitimacy and Political Recognition. *British Journal of Middle Eastern Studies*, *42*(3), 339–357. https://doi.org/10.1080/13530194.2014.949220

Withers, P.J., van Dijk, K.C., Neset, T.S., Nesme, T., Oenema, O., Rubaek, G.H., et al. (2015). Stewardship to tackle global phosphorus inefficiency: the case of Europe. Ambio 44 (Suppl. 2), 193–206. http://dx.doi.org/10.1007/s13280-014-0614-8.

World Bank. (2025). Commodity markets: Commodities Price Data (The Pink Sheet). *World Bank*. Retrieved 5 February 2025, from https://www.worldbank.org/en/research/commodity-markets

Zheng, M., Hu, Z., Liu, T. *et al.* (2024). Pathways to advanced resource recovery from sewage. *Nat Sustain* **7**, 1395–1404. https://doi.org/10.1038/s41893-024-01423-6

Zhou, K., Barjenbruch, M., Kabbe, C., Inial, G., & Remy, C. (2017). Phosphorus recovery from municipal and fertilizer wastewater: China's potential and perspective. In *Journal of Environmental Sciences (China)* (Vol. 52, pp. 151–159). Chinese Academy of Sciences. https://doi.org/10.1016/j.jes.2016.04.010

Zhou, K., Remy, C., Kabbe, C., & Barjenbruch, M. (2019). Comparative environmental life cycle assessment of phosphorus recovery with different generations of the AirPrex® systems. *International Journal of Environmental Science and Technology*, *16*(5), 2427–2440. https://doi.org/10.1007/s13762-018-1881-x

Zhu, F., Cakmak, E. K., & Cetecioglu, Z. (2023). Phosphorus recovery for circular Economy: Application potential of feasible resources and engineering processes in Europe. In *Chemical Engineering Journal* (Vol. 454). Elsevier B.V. https://doi.org/10.1016/j.cej.2022.140153

Appendix A

A1. Cost and Benefits of P Recovery Technologies from Wastewater

The costs and benefits data for the phosphorus recovery technologies were mainly taken from Egle et al. (2016). The study provides the cost of recovery for phosphorus considering a modification of a reference WWTP in central Europe, that has WWTP characteristics as those described in section 4.3 and Figure 4, considering both phosphorus removal through iron dosing (CPR) and biological removal of P (EBPR), and an incineration unit for the sludge treatment. Also, this reference system considers a WWTP of 100,000 p.e with a P load of 65,700 kg per year (1.8 g per p.e. per day) and an average of influent 200 L per p.e. per day, which are also in accordance with the descriptions in section 4.3 and Figure 4. The cost is given in euros per kg of recovered P and in euro per p.e. per year, with and without revenues and savings for Airprex, Pearl, Leachphos and Recophos, and other technologies. While the Airprex and Pearl technologies can be applied to different sizes of WWTP, Leachphos and Recophos technologies need a high mass of sewage sludge ash to be economical (Egle et al., 2016). Therefore, the analysis for these last two technologies can only be conducted for big enough WWTPs, of at least 1.75 million p.e. according to Egle et al. (2016).

The considered costs are investment costs and operational costs, and they are explicitly shown in the Egle's (2016) study. The investment costs refer to acquiring the technology, related reactors and construction needs. These are given in two ways: (1) one-off initial investments and (2) they were transformed into annual capital costs so that it was possible to have the cost of recovery per year. The latter was done by using the annuity method, considering 5% interest rate and the usual expected depreciation time of the plant components of 15 years, which is equivalent to the expected useful life for construction engineering, unless otherwise specified. This was also the time horizon considered for the CBA. The operational costs are classified into 5: resources/raw materials, personnel, energy, maintenance, disposal and they were determined by a material flow analysis of the reference WWTP.

As for the benefits, they stem from operational and from the selling of the recovered phosphorus product. The operational savings come from improved dewatering of sludge and consequent lower disposal costs and from reduced nutrient backflow of P and NH4 in the digester supernatant. The selling of the recovered product is based on the nutrient content price for struvite (Airprex and Pearl) and calcium phosphate (Leachphos), as these products didn't and still don't have a properly established market price. While for the recovered material that has properties very similar to mineral phosphorus fertilizers (Recophos), the market price of the later was used. This was pointed out as a weak point of the study. The benefits are not explicitly given in the study and were therefore calculated. The revenue from the recovered phosphorus products was done based on the method provided in the study: multiplying the nutrient present in the products (P, N, Mg, and Ca) by their common market value (P: 1.7 € /kg, N:1.1 € /kg, Mg: 0.3 € /kg, and Ca:0.1 € /kg) and the amount of recovered product, for Airprex, Pearl and Leachphos. While for Recophos the calculation used the market price at the time for single super phosphate (0.9 eur/kg). Finally, the operational benefits were calculated based on the costs with revenues and savings minus the costs without revenues and savings minus the revenue from the recovered products, for each technology.

For Airprex and Pearl , the sensitivity analysis included the different sizes of WWTPs of 100K and 500K P.E. just like Egle et al. (2016), but also for 1M and 1.75M. Since the costs and benefits were only calculated for 100K and 500K P.E. in Egle et al. (2016), the investment costs, operational costs and operational benefits had to be estimated (not the benefits stemming from revenue because those can be calculated separetely by the amount of recovered P and the selling price of the product). These facilities show economies of scale (Hernandez-Sancho et al., 2015). Therefore, scaling factors were determined for Airprex and Pearl according to the cost-to-capacity method, as shown in Equation (1) (Martin-Hernandez et al., 2024; Towler and Sinnott, 2012):

$$Cost/Benefit_{500K\ P.E.} = Cost/Benefit_{100K\ P.E.} * \left(\frac{Treatment\ capacity_{500K\ P.E.}}{Treatment\ capacity_{100K\ P.E.}}\right)^{scaling\ factor}, \text{ Eq. (1)}$$

with $Cost/Benefit$ in euros/year for operational costs and benefits or in euros for investment cost,
and $Treatment\ capacity$ in inflow P in kg/year.

For the firm-level analysis, different prices were considered for the selling of the recovered P product. For Airprex, Pearl and Leachphos, the nutrient content price was one of them (method of calculation already previously described). For Airprex, the other value used was the general maximum selling price of struvite of 0.1 eur/kg (Muys et al., 2021). For Pearl, the other value used the selling price for Crystal Green (1.0 eur/kg), which is Pearl's trademarked struvite (Muys et al., 2021). For Leachphos, the other value used was the current market price of calcium phosphate of 1.09 eur/kg (Randall et al., 2024). Since the Recophos product (16.6 %P) has a medium P content of triple superphosphate (20% P) and phosphate rock (12.6%), the minimum and maximum market prices (World Bank, 2025) for these two mineral phosphorus commodities from 2022 to 2024 were used for the sensitivity analysis.

A2. Environmental Impacts Quantification

There are multiple external benefits associated with phosphorus recovery at municipal WWTPs in the European Union. They are protecting and improving water quality - through the avoidance of eutrophication (that impacts negatively water bodies by changing water chemistry, altering diversity and amount of aquatic species, diminishing biodiversity, limiting recreational use, imposing restrictions on navigation and also possibly further economic and social impacts such as loss of fisheries resulting in job losses equity), lowering greenhouse gas emissions, reducing the use of landfills, improving food security and social equity, recycling of nutrients and better aesthetics (Chrispim et al., 2019; Hernandez-Sancho et al., 2015; Mayer et al., 2016). These impacts could be quantified through an extended life cycle assessment (LCA) and social-LCA. However, due to time restrictions the quantification of the environmental impacts of the selected technologies was done through literature research.

Manoukian et al. (2023) provides an overview of studies that quantified environmental impacts of phosphorus recovery technologies from wastewater through life cycle assessment. The table below (Appendix Table 1) provides an assessment of the studies in Manoukian et al. (2023) and others found through Scopus regarding the possibility to be integrated with the reference study of Amann et al. (2018), that is a follow-up study on Egle et al. (2016), so it has the same boundaries as the study that quantified the costs and benefits of the technologies when compared to the reference system (100.000 PE, central European countries, waste activated sludge, phosphorus removal through EBPR or chemicals addition, and incineration of sewage sludge).

It is important that the selected studies have the same boundaries and reference system as the reference study of Egle et al. (2016) because the conclusions of an LCA study can vary depending on these factors. System boundaries define what processes are included in the analysis. A narrower boundary can focus on a specific stage, while a broader boundary includes upstream and downstream impacts, such as raw material extraction, transportation, and waste management. Given that this study is analyzing the environmental impacts of changing a business-as-usual practice (reference system), it is essential that the reference system in the LCA studies are the most comparable possible with the reference system of the reference study, to ensure that the quantified impacts reflect the real-life.

Appendix Table 1. Compatibility assessment between reference study and others on the life cycle assessment of phosphorus recovery from wastewater (boundaries and reference system).

			Step Included in the Environmental Impact Assessment (in orange)								Usable
Study	**Where Scenario**	**Scenario**	**wastewater treatment**	**construction due to adaptation**	**sludge treatment**	**waste treatment (sludge)**	**agricultural application**	**sludge disposal**	**transport**	**offset**	
Amann et al., 2018	**Austria; landlocked central EU countries**	reference EU WWTP with EBPR or Chem P removal + 18 P recovery techs		Construction technology not accounted for because of no available information. But previous studies indicated minor significance of th is phase					transport of sludge, wastes (fly ash, filter cake, technology wastes) and the recovered material to agriculture.	Production of net energy and resources (i.e. electricity, heat, by-products, P-fertilizer, N-fertilizer) is accounted for by taking the avoided burden approach, assigning energy or emission credits to the studied systems for substitution of these products.	Yes. It is the reference scenario for which the costs were calculated Egle et al. (2016). But impacts are not presented per steps, so if other references have only a part of the process, say only the sludge line treatment and disposal, it is not possible to integrate that information.
Remy et al. (2015)	**Austria; landlocked central EU countries**	reference EU WWTP with EBPR or Chem P removal, monoincineration of sludge + 10 P recovery techs						No further emissions into the environment are assumed from the deposit, as incineration ash as hazardous material should be deposited in specialized landfills or underground mines, prohibiting any leaching or emission of pollutants from the ash.	transport of sludge, wastes (fly ash, filter cake, technology wastes)	credits for energy and heat	No. Boundaries are different, it doesn't account for the wastewater treatment. Since there wasn't a study that gives the impacts of the wastewater treatment alone, it is not possible to use this data.
Zhou et al. (2019)	**Berlin Wassmannsdorf**	Reference scenario (normal sludge treatment for EU countries); 1 recovery tech (2 generations of airprex)							sludge transport	credits for energy, heat, P, N	No. Boundaries are different, it doesn't account for the wastewater treatment. Since there wasn't a study that gives the impacts of the wastewater treatment alone, it is not possible to use this data.
Ravi et al. (2022)	**Belgium, Flanders**	reference syst w struvite recovery									No. Boundaries are different, and impact is not given by steps.
		reference system w use of P fertilizer (includes system of mineral P production)									
		3 types of treatment of sludge (co- and mono ncineration, land use application of biosolids)					for 2 of the scenarios			electricity, conventional N and P fertilizer application	
Pradel and Aissani (2019)	**Europe**	EBPR and some P recovery technologies									No. The reference system includes wastewater transport to the WWTP and it doesn't give the impacts per step (to be able to exclude the wastewater transport).

Pradel et al. (2020)	**Europe**	Scenarios from Pradel and Aissani (2019), with extra land application of sewage sludge									No. (Same reason as above because it is a follow-up study)
Lederer and Rechberger (2010)	**Europe**	normal sludge treatment and monoincineration									No, the reference scenario is formal normal sludge treatment, not activated sludge.
Long et al. (2024)	**Austria**	they also consider agricultural disposal and don't show the results separetly									No. Specific for austria, all wwtp and possible scenarios for p recovery, so not possible to disintegrate the data for one WWTP.
Studies that didn't have the pre-requisite of same reference system											
Goel et al (2021)	No. Reference System doesn't have EBPR or Chemical P removal										
Linderholm et al. (2012)	No. System boundaries are not completely clear.										
Gong et al (2024)	No. Analysis of life cycle inventories, not the life cycle assessment.										
Fang et al. (2016)	No. P recovery technologies were not considered in the study.										
Sena et al. (2021)	No. The reference WWTPhas EBPR, but it is in the US and there is spreading of biosolids in agriculture rather than incineration.										
Rufi-Salis et al. (2020)	No. The reference WWTP has no EBPR or chem p removal.										
Rashid et al. (2020)	No. The reference WWTP has no EBPR or chem p removal.										
Rodriguez-Garcia et al (2014)	No. The phosphorus recovery technologies are not clearly specified.										
Rufi-Salis et al (2022)	No. The reference WWTP has no EBPR or chem p removal.										
Sorensen et al. (2015)	No. The reference system considered is ''use of sludge on agricultural land'' - not the system being analyzed.										
Lundinet et al. (2004)	No. The study considers recovery technologies that are not the ones in this thesis.										

Given that none of the assessed studies have boundaries or reference systems that can be integrated with the reference study of Amann et al. (2018), only the data from the former was included as the quantification of the environmental impacts of the phosphorus recovery technologies.

The environmental indicators assessed by Amman et al. (2018) are cumulative energy demand (CED), global warming potential (GWP) and acidification potential (AP). The CED accounts for direct and indirect energy demand. Since in the study the GWP includes emissions from energy use (e.g. combustion of fossil fuels), the inclusion of CED and GWP could lead to double counting of energy related impacts. To avoid this, the CED indicator was not considered in the calculations. Egle et al. (2016) also quantifies the damage unit related to the heavy metals content on the recovered P product. Given that the agricultural application is not part of the considered scope, it was excluded from the analysis. Appendix Table *2* shows the GWP and AP for the reference system and the selected phosphorus recovery technologies.

Appendix Table 2. Environmental Indicators of climate change (GWP - Global Warming Potential) and acidification potential for the reference system of 100.000.p.e., in an imaginary WWTP in Central Europe, from Amann et al. (2018).

Parameter	Value	Unit
GWP Reference System	9	kg CO2e PE-1year-1
GWP Airprex	7.6	kg CO2e PE-1year-1
GWP Pearl	7.8	kg CO2e PE-1year-1
GWP Leachphos	8.8	kg CO2e PE-1year-1
GWP Recophos	3.8	kg CO2e PE-1year-1
Acidification potential Reference System	42	g SO2e PE-1 year-1
Acidification potential Airprex	32.9	g SO2e PE-1 year-1
Acidification potential Pearl	31.7	g SO2e PE-1 year-1
Acidification potential Leachphos	39.6	g SO2e PE-1 year-1
Acidification potential Recophos	18.6	g SO2e PE-1 year-1

A3. Environmental Pricing

Many environmental goods are not normally valued due to the public good characteristic of many environmental resources, meaning that they don't have established market prices and require alternative valuation methods (Hernandez-Sancho et al., 2015). The valuation of these goods reflects the social marginal value (the willingness-to-pay for less environmental pollution) of environmental impacts, that are not included in the economy (environmental externalities). Appendix Table 4 and 5 show the monetization factors for climate change and acidification potential, which are the environmental impact categories that were considered in this study, for two benchmark references True Price (2023) and Environmental Prices Handbook EU28 (de Bruyn et al., 2018) and a specific study that compiled monetization factors for their social cost benefit analysis on phosphorus recovery from wastewater (Farago et al., 2022).

Appendix Table 3. Monetization factors fot Climate Change.

Converted Data found for Valuation of Environmental Impact all in 2024euros Climate change			
Environmental Prices Handbook EU28	Climate change	0.072	€/kg CO2-eq.
Farago et al. (2022)	climate change mean	0.19	€/kg CO2-eq.
Farago et al. (2022)	climate change min	0.03	€/kg CO2-eq.
Farago et al. (2022)	climate change max	1.07	€/kg CO2-eq.
True Price (2023)	Climate change	0.17	€/kg CO2-eq.

Appendix Table 4. Monetization factors for Acidification.

Converted Data found for Valuation of Environmental Impact all in 2024euros Acidification Potential			
Environmental Prices Handbook EU28	Acidification	6.313	€/kg SO2-eq.
True Price (2023)	Acidification	5.082	€/kg SO2-eq.
Average	Acidification	5.698	€/kg SO2-eq.

A4. Firm-Level CBA Results

Appendix Table 5. Firm Level CBA Results

	WWTP size	100K p.e.	500K p.e.	1M p.e.	1.75M p.e.
Airprex	Firm level - only operational benefits				
	NPV (3.8%)	EUR 558,112.30	EUR 2,214,000.95	EUR 4,182,768.73	EUR 6,910,593.18
	NPV (5.2%)	EUR 477,516.96	EUR 1,912,908.63	EUR 3,634,474.06	EUR 6,026,485.70
	NPV (12.2%)	EUR 204,751.58	EUR 893,897.28	EUR 1,778,835.61	EUR 3,034,328.51
	Firm level - operational benefits plus revenue based on struvite market price				
	NPV (3.8%)	EUR 570,479.21	EUR 2,275,835.52	EUR 4,306,437.86	EUR 7,127,014.15
	NPV (5.2%)	EUR 488,748.96	EUR 1,969,068.64	EUR 3,746,794.08	EUR 6,223,045.73
	NPV (12.2%)	EUR 212,142.61	EUR 930,852.44	EUR 1,852,745.93	EUR 3,163,671.57
	Firm level - operational benefits plus revenue based on nutrient content				
	NPV (3.8%)	EUR 599,948.69	EUR 2,423,182.91	EUR 4,601,132.65	EUR 7,642,730.03
	NPV (5.2%)	EUR 515,514.03	EUR 2,102,893.98	EUR 4,014,444.75	EUR 6,691,434.41
	NPV (12.2%)	EUR 229,754.91	EUR 1,018,913.97	EUR 2,028,868.99	EUR 3,471,886.92
Pearl	Firm level - only operational benefits				
	NPV (3.8%)	-EUR 222,512.54	EUR 203,067.76	EUR 793,517.42	EUR 1,703,362.28
	NPV (5.2%)	-EUR 359,471.61	-EUR 8,017.84	EUR 510,828.08	EUR 1,321,970.20
	NPV (12.2%)	-EUR 822,993.39	-EUR 722,412.08	-EUR 445,900.54	EUR 31,193.81
	Firm level - operational benefits plus revenue based on nutrient content				
	NPV (3.8%)	-EUR 164,807.17	EUR 491,594.60	EUR 1,370,571.09	EUR 2,713,206.22
	NPV (5.2%)	-EUR 307,061.86	EUR 254,030.92	EUR 1,034,925.59	EUR 2,239,140.84
	NPV (12.2%)	-EUR 788,506.03	-EUR 549,975.27	-EUR 101,026.91	EUR 634,722.66
	Firm level - operational benefits plus revenue based on Ostara Pearl struvite price				
	NPV (3.8%)	-EUR 51,934.43	EUR 1,055,958.29	EUR 2,499,298.48	EUR 4,688,479.14
	NPV (5.2%)	-EUR 204,547.44	EUR 766,603.00	EUR 2,060,069.76	EUR 4,033,143.13
	NPV (12.2%)	-EUR 721,048.13	-EUR 212,685.76	EUR 573,552.11	EUR 1,815,235.94
Leachphos	Firm level - only operational benefits				
	NPV (3.8%)				-EUR 20,015,630.54
	NPV (5.2%)				-EUR 20,510,338.99
	NPV (12.2%)				-EUR 22,184,621.21
	Firm level - operational benefits plus revenue based on nutrient content				
	NPV (3.8%)				-EUR 15,782,586.10
	NPV (5.2%)				-EUR 16,665,760.69
	NPV (12.2%)				-EUR 19,654,760.58
	Firm level - operational benefits plus revenue based on calcium phosphate market price				
	NPV (3.8%)				-EUR 10,445,494.73
	NPV (5.2%)				-EUR 11,818,453.74
	NPV (12.2%)				-EUR 16,465,071.09
Recophos	Firm level - only operational benefits				
	NPV (3.8%)				-EUR 15,964,328.03
	NPV (5.2%)				-EUR 15,366,616.31
	NPV (12.2%)				-EUR 13,343,731.69
	Firm level - operational benefits plus revenue based on min market price				
	NPV (3.8%)				-EUR 13,209,475.93
	NPV (5.2%)				-EUR 12,864,576.75
	NPV (12.2%)				-EUR 11,697,306.29
	Firm level - operational benefits plus revenue based on max market price				
	NPV (3.8%)				-EUR 8,691,518.49
	NPV (5.2%)				-EUR 8,761,231.89
	NPV (12.2%)				-EUR 8,997,168.64

A5. Societal CBA Results

Appendix Table 6. Social CBA Results.

	WWTP SIZE	100K p.e.	500K p.e.	1M p.e.	1.75M p.e.
Airprex	Social CBA - min external benefits				
Airprex	*NPV (3.5%)*	EUR 53,933,004.37	EUR 269,064,642.46	EUR 537,871,453.17	EUR 940,848,161.77
Airprex	***NPV (4.5%)***	EUR 50,268,846.13	EUR 250,820,441.85	EUR 501,423,563.25	EUR 877,121,041.82
Airprex	*NPV (5.5%)*	EUR 46,962,219.03	EUR 234,356,423.66	EUR 468,532,085.24	EUR 819,612,111.43
Airprex	Social CBA - average external benefits				
Airprex	*NPV (3.5%)*	EUR 54,192,902.36	EUR 270,364,132.40	EUR 540,470,433.06	EUR 945,396,376.59
Airprex	***NPV (4.5%)***	EUR 50,511,191.07	EUR 252,032,166.59	EUR 503,847,012.72	EUR 881,362,078.40
Airprex	*NPV (5.5%)*	EUR 47,188,723.68	EUR 235,488,946.90	EUR 470,797,131.73	EUR 823,575,942.78
Airprex	Social CBA - max external benefits				
Airprex	*NPV (3.5%)*	EUR 68,518,660.10	EUR 341,992,921.09	EUR 668,173,115.78	EUR 1,196,097,137.01
Airprex	***NPV (4.5%)***	EUR 63,869,412.96	EUR 318,823,276.02	EUR 622,924,886.45	EUR 1,115,130,961.39
Airprex	*NPV (5.5%)*	EUR 59,673,817.26	EUR 297,914,414.81	EUR 582,091,764.35	EUR 1,042,065,080.48
Pearl	Social CBA - min external benefits				
Pearl	*NPV (3.5%)*	EUR 60,313,617.52	EUR 302,772,972.65	EUR 605,900,718.67	EUR 1,060,614,473.51
Pearl	***NPV (4.5%)***	EUR 56,124,321.20	EUR 282,182,597.96	EUR 564,824,823.49	EUR 988,816,839.87
Pearl	*NPV (5.5%)*	EUR 52,343,796.51	EUR 263,601,334.19	EUR 527,756,918.98	EUR 924,024,878.17
Pearl	Social CBA - average external benefits				
Pearl	*NPV (3.5%)*	EUR 60,536,387.22	EUR 303,886,821.17	EUR 608,128,415.73	EUR 1,064,512,943.35
Pearl	***NPV (4.5%)***	EUR 56,332,045.44	EUR 283,221,219.16	EUR 566,902,065.89	EUR 992,452,014.08
Pearl	*NPV (5.5%)*	EUR 52,537,943.35	EUR 264,572,068.40	EUR 529,698,387.39	EUR 927,422,447.90
Pearl	Social CBA - max external benefits				
Pearl	*NPV (3.5%)*	EUR 76,361,612.89	EUR 383,012,949.50	EUR 766,380,672.39	EUR 1,341,454,392.51
Pearl	***NPV (4.5%)***	EUR 71,088,463.89	EUR 357,003,311.42	EUR 714,466,250.41	EUR 1,250,689,336.99
Pearl	*NPV (5.5%)*	EUR 66,329,843.72	EUR 333,531,570.24	EUR 667,617,391.07	EUR 1,168,780,704.32
Leachphos	Social CBA - min external benefits				
Leachphos	*NPV (3.5%)*				EUR 235,830,909.94
Leachphos	***NPV (4.5%)***				EUR 218,187,414.42
Leachphos	*NPV (5.5%)*				EUR 202,265,487.37
Leachphos	Social CBA - average external benefits				
Leachphos	*NPV (3.5%)*				EUR 236,480,654.91
Leachphos	***NPV (4.5%)***				EUR 218,793,276.79
Leachphos	*NPV (5.5%)*				EUR 202,831,748.99
Leachphos	Social CBA - max external benefits				
Leachphos	*NPV (3.5%)*				EUR 299,599,285.81
Leachphos	***NPV (4.5%)***				EUR 277,648,989.15
Leachphos	*NPV (5.5%)*				EUR 257,840,498.13
Recophos	Social CBA - min external benefits				
Recophos	*NPV (3.5%)*				EUR 2,391,426,475.37
Recophos	***NPV (4.5%)***				EUR 2,229,275,526.95
Recophos	*NPV (5.5%)*				EUR 2,082,946,497.63
Recophos	Social CBA - average external benefits				
Recophos	*NPV (3.5%)*				EUR 2,408,319,844.68
Recophos	***NPV (4.5%)***				EUR 2,245,027,948.56
Recophos	*NPV (5.5%)*				EUR 2,097,669,299.77
Recophos	Social CBA - max external benefits				
Recophos	*NPV (3.5%)*				EUR 3,081,344,952.03
Recophos	***NPV (4.5%)***				EUR 2,872,598,153.38
Recophos	*NPV (5.5%)*				EUR 2,684,219,875.49

References

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., & Egle, L. (2018). Environmental impacts of phosphorus recovery from municipal wastewater. *Resources, Conservation and Recycling*, *130*, 127–139. https://doi.org/10.1016/j.resconrec.2017.11.002

de Bruyn, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., Vergeer, R., & Ahdour, S. (2018). *Environmental Prices Handbook EU28 versionN54-Environmental Prices Handbook Environmental Prices Handbook EU28 version*.

Chrispim, M. C., Scholz, M., & Nolasco, M. A. (2019). Phosphorus recovery from municipal wastewater treatment: Critical review of challenges and opportunities for developing countries. In *Journal of Environmental Management* (Vol. 248). Academic Press. https://doi.org/10.1016/j.jenvman.2019.109268

Egle, L., Rechberger, H., Krampe, J., & Zessner, M. (2016). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Science of the Total Environment*, *571*, 522–542. https://doi.org/10.1016/j.scitotenv.2016.07.019

Fang, L. L., Valverde-Pérez, B., Damgaard, A., Plósz, B. G., & Rygaard, M. (2016). Life cycle assessment as development and decision support tool for wastewater resource recovery technology. *Water Research*, *88*, 538–549. https://doi.org/10.1016/j.watres.2015.10.016

Faragò, M., Damgaard, A., Logar, I., & Rygaard, M. (2022). Life Cycle Assessment and Cost-Benefit Analysis of Technologies in Water Resource Recovery Facilities: The Case of Sludge Pyrolysis. *Environmental Science and Technology*, *56*(24), 17988–17997. https://doi.org/10.1021/acs.est.2c06083

Goel, S., Kansal, A., & Pfister, S. (2021). Sourcing phosphorus for agriculture: Life cycle assessment of three options for India. *Resources, Conservation and Recycling*, *174*. https://doi.org/10.1016/j.resconrec.2021.105750

Gong, Y., Zheng, X., Liu, G., & Lam, K. L. (2024). Compiling life cycle inventories for wastewater-derived products. *Water Research*, *255*. https://doi.org/10.1016/j.watres.2024.121439

Hernández-Sancho, F., Lamizana-Diallo, B., Mateo-Sagasta, J., & Qadir, M. (2015). *Economic Valuation of Wastewater - The cost of action and the cost of no action*. United Nations Environmental Programme. https://www.unep.org/resources/report/economic-valuation-wastewater-cost-action-and-cost-no-action#:~:text=Report-,Economic%20Valuation%20of%20Wastewater:%20The%20Cost%20of%20Action,the%20Cost%20of%20No%20Action&text=This%20book%20presents%20the%20results,projects%2C%20therefore%20underestimating%20total%20benefits

Lederer, J., & Rechberger, H. (2010). Comparative goal-oriented assessment of conventional and alternative sewage sludge treatment options. *Waste Management*, *30*(6), 1043–1056. https://doi.org/10.1016/j.wasman.2010.02.025

Linderholm, K., Tillman, A. M., & Mattsson, J. E. (2012). Life cycle assessment of phosphorus alternatives for Swedish agriculture. *Resources, Conservation and Recycling*, *66*, 27–39. https://doi.org/10.1016/j.resconrec.2012.04.006

Long, A., Weber, N., Krampe, J., Peer, S., Rechberger, H., Zessner, M., & Zoboli, O. (2024). Multi-criteria analysis of strategies towards sustainable recycling of phosphorus from sewage sludge in Austria. *Journal of Environmental Management*, *362*. https://doi.org/10.1016/j.jenvman.2024.121339

Lundin, M., Olofsson, M., Pettersson, G. J., & Zetterlund, H. (2004). Environmental and economic assessment of sewage sludge handling options. *Resources, Conservation and Recycling*, *41*(4), 255–278. https://doi.org/10.1016/j.resconrec.2003.10.006

Manoukian, L., Metson, G. S., Hernández, E. M., Vaneeckhaute, C., Frigon, D., & Omelon, S. (2023). Forging a cohesive path: Integrating life cycle assessments of primary-origin phosphorus fertilizer production and secondary-origin recovery from municipal wastewater. In *Resources, Conservation and Recycling* (Vol. 199). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2023.107260

Martin-Hernandez, E., Omelon, S., Vaneeckhaute, C., & Ruiz-Mercado, G. J. (2024). Phosphorus Recovery in Municipal Wastewater and Socioeconomic Impacts in Canada and the United States. *ACS ES and T Water*. https://doi.org/10.1021/acsestwater.4c00569

Mayer, B. K., Baker, L. A., Boyer, T. H., Drechsel, P., Gifford, M., Hanjra, M. A., Parameswaran, P., Stoltzfus, J., Westerhoff, P., & Rittmann, B. E. (2016). Total value of phosphorus recovery. *Environmental Science & Technology*, *50*(13), 6606–6620. https://doi.org/10.1021/acs.est.6b01239

Muys, M., Phukan, R., Brader, G., Samad, A., Moretti, M., Haiden, B., Pluchon, S., Roest, K., Vlaeminck, S. E., & Spiller, M. (2021). A systematic comparison of commercially produced struvite: Quantities, qualities and soil-maize phosphorus availability. *Science of the Total Environment*, *756*. https://doi.org/10.1016/j.scitotenv.2020.143726

Pradel, M., & Aissani, L. (2019). Environmental impacts of phosphorus recovery from a "product" Life Cycle Assessment perspective: Allocating burdens of wastewater treatment in the production of sludge-based phosphate fertilizers. *Science of the Total Environment*, *656*, 55–69. https://doi.org/10.1016/j.scitotenv.2018.11.356

Pradel, M., Lippi, M., Daumer, M. L., & Aissani, L. (2020). Environmental performances of production and land application of sludge-based phosphate fertilizers—a life cycle assessment case study. *Environmental Science and Pollution Research*, *27*(2), 2054–2070. https://doi.org/10.1007/s11356-019-06910-4

Randall, D. G., Jalava, J., Vinnerås, B., & Simha, P. (2024). Phosphorus recovery as vivianite and amorphous calcium phosphate from high-load industrial wastewater. *Frontiers in Environmental Science*, *12*. https://doi.org/10.3389/fenvs.2024.1491220

Rashid, S. S., Liu, Y. Q., & Zhang, C. (2020). Upgrading a large and centralised municipal wastewater treatment plant with sequencing batch reactor technology for integrated nutrient removal and phosphorus recovery: Environmental and economic life cycle performance. *Science of the Total Environment*, *749*. https://doi.org/10.1016/j.scitotenv.2020.141465

Ravi, R., Beyers, M., Bruun, S., & Meers, E. (2022). Life cycle assessment of struvite recovery and wastewater sludge end-use: A Flemish illustration. *Resources, Conservation and Recycling*, *182*. https://doi.org/10.1016/j.resconrec.2022.106325

Remy, C., Boulestreau, M., Warneke, J., Jossa, P., Kabbe, C., & Lesjean, B. (2016). Evaluating new processes and concepts for energy and resource recovery from municipal wastewater with life cycle assessment. *Water Science and Technology*, *73*(5), 1074–1080. https://doi.org/10.2166/wst.2015.569

Rodriguez-Garcia, G., Frison, N., Vázquez-Padín, J. R., Hospido, A., Garrido, J. M., Fatone, F., Bolzonella, D., Moreira, M. T., & Feijoo, G. (2014). Life cycle assessment of nutrient removal technologies for the treatment of anaerobic digestion supernatant and its integration in a wastewater treatment plant. *Science of the Total Environment*, *490*, 871–879. https://doi.org/10.1016/j.scitotenv.2014.05.077

Rufí-Salís, M., Brunnhofer, N., Petit-Boix, A., Gabarrell, X., Guisasola, A., & Villalba, G. (2020). Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions. *Science of the Total Environment*, *737*. https://doi.org/10.1016/j.scitotenv.2020.139783

Rufí-Salís, M., Petit-Boix, A., Leipold, S., Villalba, G., Rieradevall, J., Moliné, E., Gabarrell, X., Carrera, J., & Suárez-Ojeda, M. E. (2022). Increasing resource circularity in wastewater treatment: Environmental implications of technological upgrades. *Science of the Total Environment*, *838*. https://doi.org/10.1016/j.scitotenv.2022.156422

Sena, M., Seib, M., Noguera, D. R., & Hicks, A. (2021). Environmental impacts of phosphorus recovery through struvite precipitation in wastewater treatment. *Journal of Cleaner Production*, *280*. https://doi.org/10.1016/j.jclepro.2020.124222

Sørensen, B. L., Dall, O. L., & Habib, K. (2014). Environmental and resource implications of phosphorus recovery from waste activated sludge. *Waste Management*, *45*, 391–399. https://doi.org/10.1016/j.wasman.2015.02.012

Towler, G., & Sinnott, R. (2012). *Chemical engineering design: Principles, practice and economics of plant and process design*. Elsevier.

True Price. (2023). *MONETISATION FACTORS FOR TRUE PRICING*. www.trueprice.org.

World Bank. (2025). Commodity markets: Commodities Price Data (The Pink Sheet). World Bank. Retrieved 5 February 2025, from https://www.worldbank.org/en/research/commodity-markets

Zhou, K., Barjenbruch, M., Kabbe, C., Inial, G., & Remy, C. (2017). Phosphorus recovery from municipal and fertilizer wastewater: China's potential and perspective. In *Journal of Environmental Sciences (China)* (Vol. 52, pp. 151–159). Chinese Academy of Sciences. https://doi.org/10.1016/j.jes.2016.04.010

Appendix B

Excel file