Phosphorus flows mapping and economic analysis for its recovery in the province of Ontario, Canada

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Abstract

The dual dimension of the anthropogenic use of phosphorus, i.e., its key role in the food production system and the negative environmental impacts associated with the phosphorus used in intensive agricultural techniques, has been stated by the United Nations Environment Assembly. In addition, phosphorus is a non-renewable material which reserves are concentrated in a few number of regions, making global supply chains vulnerable to regional events and conflicts. As a consequence, the recovery and recycling of phosphorus is not just a desirable but also a necessary approach to assure a sustainable, reliable, and sovereign food production system. In this work we map the phosphorus flows through the economic sectors of the Canadian province of Ontario, and phosphorus recovery and recycling opportunities are identified. These mainly belong to the agricultural sector, including manure (30.5 kt/year) and slaughterhouse waste (3.7 kt/year), although significant amounts of P are also found in food and organic waste, including municipal wastewater (6.4 kt/year). Different scenarios are studied to determine the amount of phosphorus that could be recovered within the province considering according with the technology readiness level of different phosphorus recovery processes, as well as the costs associated with phosphorus recovery Add some more numbers here. Finally, we discuss the implications that would be derived from implementing active phosphorus recovery and recycling approaches regarding phosphorus supply and use in Ontario.

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1. Introduction

Phosphorus is an essential for production of food which has been intensively used for crop and livestock production since the development of synthetic fertilizers in the XIX and XX centuries (Samreen and Kausar, 2019). The combination of synthetic fertilizers with other modern intensive agricultural techniques have increased the productivity of agriculture and farming industries (Pingali, 2012). However, the intensive use of fertilizers in agriculture has resulted in the over-application of phosphorus in many regions worldwide REF, while the run of intensive livestock production facilities, also known as concentrated animal feeding operations (CAFOs) (U.S. Department of Agriculture, 2011), result in important difficulties in the management of the large amounts of manure produced, which is often spread in lands in the vicinity of CAFOs, which also leads to the accumulation of phosphorus in soil. Soil acts as a phosphorus reservoir (Ehlert et al., 2003), building-up a legacy P that can be used for future crops, but also can be transported to waterbodies by erosion and runoff leading to the eutrophication of aquatic ecosystems.

The dual dimension of the anthropogenic use of phosphorus, i.e., its key role in the food production system and the negative environmental impacts associated with the phosphorus used in intensive agricultural techniques, as it has been stated by the United Nations Environment Assembly in the resolution UNEP/EA.5/Res.2 (United Nations Environment Programme, 2022). An additional factor to be considered for addressing the phosphorus challenge is the non-renewable nature of phosphorus, since the phosphorus consumed is not replenished by natural means at human time scale, and there is currently no known synthetic substitute for this material (Cordell et al., 2009). Since the global phosphorus reserves are concentrated in a few number of regions, the supply of phosphorus from a limited number of global supply chains lacks resiliency and it has been proven that it can be globally disrupted by regional events and conflicts, resulting geopolitical tensions (Food and Agriculture Organization of the United Nations, 2022). As a consequence, the recovery and recycling of phosphorus is not just a desirable but also a necessary approach to assure a sustainable, reliable, and sovereign food production system.

Although the main uses of phosphorus are in the agri-food sector, phosphorus is also involved in other industrial activities, including steel, chemical, and forestry industries. Henceforth, phosphorus is a key material for many aspects of human development. As a result, mapping the phosphorus flows involved in human activities to detect opportunities for recovery and recycling is essential for, in a second stage, assess amount of phosphorus that is viable to recover, the economical costs involved, and the enhancement in terms of resiliency of the regional food production system, savings from the reduction of phosphorus imports, and the mitigation of phosphorus pollution on the region implementing strategies for phosphorus recovery and recycling. The quantification of phosphorus flows has been addressed in previous works in the literature for certain sectors such as the agri-food sector (Boh and Clark, 2020; Zhou et al., 2021; Nesme et al., 2018). Additionally, studies on the global phosphorus flows have also been performed (Villalba et al., 2008; Chen and Graedel, 2016), although these studies tend to have a low flow resolution since these are aggregated by major sectors. Additionally, the works quantifying phosphorus often include qualitative recommendations to improve the phosphorus use efficiency and recycling (Van Dijk et al., 2016; Senthilkumar et al., 2012), but often they do not include quantitivae assessments on the amount of phopshorus which recovery is feasible along with the costs involved. Conversely, those works focused on estimating the recoverable phosphorus and the associated recovery cost target specific flows, lacking a holistic perspective of the phosphorus flows in the various human activities (Martín-Hernández et al., 2021; Sampat et al., 2018).

In this work, we intend to perform a holistic approach to phosphorus management, recovery, and recycling usingin the Canadian province of Ontario. In a first stage, we proceed to map the phosphorus flows involved in the economical sectors of Ontario, i.e., the agricultural, industrial, and urban sectors. This data is used in a second stage to identify the flows in which phosphorus recovery is feasible, estimating the amount of phosphorus that could be recovered within the province considering different phosphorus recovery technologies with technology readiness levels equal or above 6, as well as the costs associated with phosphorus recovery. Finally, we discuss the implications that would be derived from implementing active phosphorus recovery and recycling approaches regarding phosphorus supply and use in Ontario.

2. Methods

2.1. Spatial boundaries and resolution

Phosphorus flows have been mapped within the Canadian province of Ontario, and thus the political borders of Ontario has been considered as the boundaries for the material flow analysis (MFA) performed (Brunner and Rechberger, 2016). In those cases where the data was availbale, the distribution of phosphorus flows within Ontario has also been studied at Census Division level (Statistics Canada – Statistique Canada, 2017). The database collecting the IDs of Ontario Census Divisions, their names, and geospatial information is taken from Opendatasoft (2019).

Ask Melissa if we can reproduce the maps in the supplementary material

ADD MAP WITH CENSUS DIVISIONS????

2.2. Temporal boundaries

The study has being performed for year 2019 since the most of data required is available for this year. In addition, the temporal evolution of the largest phosphorus flows, i.e., agricultural and wastewater phosphorus flows, has been studied for a period of 13 years from 2007 to 2019.

2.3. Estimation of phosphorus flows

The estimation of phosphorus flows within the Ontario's agricultural sectors is based on the methodology used in Pollution Probe (2022). It is based on the use open data sources, often from governmental institutions, complemented with information from scientific articles when needed. The particular procedure followed for each flow depends on the information publicly available. In the next sections we depict the main lines of the estimating procedure for each sector, while we refer the reader to Pollution Probe (2022) for a more comprehensive description of the procedure followed for estimating each phosphorus flow.

2.3.1. Agricultural sector

Phosphorus flows in the agricultural sector are estimated based on production data of livestock and crop products, as well as data on fertilizer application.

For those production data were not available, a number of different methods were used to estimate the P flow based on approaches established in the literature. For example, P inflows associated with synthetic fertilizers could be directly estimated based on application data reported in the Fertilizer Shipments Survey (FSS).37 Conversely, P flows associated with manure were determined indirectly by accounting for the magnitude from which the flow of P could be derived. In this case,

Phosphorus in livestock imports and exports is estimated from livestock trading data REF, multiplying the number of animals by the concentration of phosphorus in the different types of livestock REF,

Phosphorus in livestock feeding and manure is estimated based on the number and type of animals reported for Ontario at Census Division level in the Census of Agriculture REF!, multiplied by the phosphorus feeding requirements REF, and concentration of phosphorus in manure REF. The Census of Agriculture is published by Statistics Canada every five years (i.e., 2001, 2006, 2011, and 2016) for cattle52 REF, sheep53 REF, swine54 REF, poultry55 REF, and other livestock56 REF, with the exception of rabbits, where data is not available prior to 2009. The number of animals for the years in between census reporting have been estimated using a linear interpolation. We assumed that the number of animals reported is throughout the year (i.e., the animals culled are replaced by new ones). However, in the case of broilers and turkeys, the number of animals reported by the livestock census have been reduced by a factor of 0.68 (broilers) and 0.80 (turkeys), since these animals have life cycles of 43 and 80 days respectively, meaning barns are empty for 20 days between cycles. 305 REF

Phosphorus contained in meat and slaughterhouse waste is based on the number of animals slaughtered reported by both federally and provincially licensed meat plants.59, 60 REF multiplied by the concentration of phosphorus in carcasses REF.

Phosphorus flows associated with the production of milk and eggs is based on provincial production data, multiplying these products by their average phosphorus concentration 57, 58 REF.

Phosphorus in fertilizer applied to open fields in Ontario is estimated based on the amount of fertilizer products traded to Ontario's agricultural markets containing P 100 REF. The distribution of phosphorus fertilizers among the Census Division of the province is based on the fraction of fertilized area of each census division, i.e., dividing the reported area of land fertilized for each census division by the total fertilized area of land in Ontario, removing the areas that correspond with greenhouse crops101, 102 103 REF. Regarding manure, we assume that all of the manure generated by livestock is applied in crop fields 50 REF.

The uptake of phosphorus by crops is determined based on the area used in each Census Division to grow each type of crops by census division104, 105, 106 and its yield107, 108 multiplied by the specific P content for each crop type.109, 110. The phosphorus uptake by crops is divided according to whether it uptake in the grain, fruit or vegetable, or straw and stover components of each type of crop. This is necessary to determine the amount of phosphorus that flows within food or feed (i.e.,grains, fruits and vegetables) while straw and stover remain in the field after harvesting as crop residues.

A fraction of the phosphorus applied to crop fields as manure of synthetic fertilizer is lost through erosion, runoff, and drainage. This transportation of phosphorus depends on a range of factor, including the amount of phosphorus applied; soil composition, texture, and slope; and precipitation, resulting in a complex and data-intensive process for estimating the phosphorus transported out of the crop fields. As an approximation, we have estimated the phosphorus losses by using export coefficients determined for crop fields in Ontario 112 REF 113 REF corrected to account for both surface and subsurface runoffs for synthetic fertilizers (1.267 kg/ha/year), and liquid and solid manure (2.548 kg/ha/year and 1.717 kg/ha/year respectively) 113 REF (Pollution Probe, 2022).

A fraction of the P supplied to crop fields is not taken up by the plants and remains in soil, resulting in the accumulation of P over time as a result of synthetic fertilizer and manure over over sustained periods of time, often applying phosphorus in greater quantities than crops require to ensure satisfactory yields 132 REF. This buildup is often referred to as “legacy P”, and it is estimated as the balance between phosphorus inflows to crop fields (application of manure and synthetic fertilizers) and outflows (crop food and feed products, crop residues, and phosphorus losses).

Regarding greenhouse crops, the data available was limited, resulting in an estimation of phosphorus applied as synthetic fertilizers based on the sum of phosphorus uptake by greenhouse crops (i.e., tomatoes, peppers, and cucumbers)119 and the phosphorus releases from greenhouse irrigation systems (greenhouse nutrient feedwater systems (GNF) REF ONTARIO) systems. The phosphorus uptake by greenhouse crops is determined by multiplying the production of greenhouse crops 120 REF by the phosphorus content of each vegetable type 121, 122 REF. The phosphorus releases from the GNF systems was estimated based on the average concentration of phosphorus in GNF outlet streams of Ontario (33.6 mg/L) 123 REF and the total water discharges from GNF systems 124 REF, assuming that water discharges from GNF systems is equivalent to 25% of the total water applied in greenhouses, which corresponding with the worst-case scenario of no water recirculation in the GNF system. The average water consumption in greenhouses in Ontario was assumed to be 1,000 L/m2/year 125 REF. We have also estimated the phosphorus releases from the seasonal workers live in households in the vicinity of the greenhouses that may use septic systems, considering that the seasonal labour force in Ontario greenhouses is estimated to be 6,699 workers 126 REF, and an average phosphorus load rate of f 0.0156 kg P/person/week from septic systems 128 REF.

REVISAR POR SIDNEY Food imports and exports (other than livestock) are estimated scaling each type of food traded in Canada (Statistics Canada - Statisque Canada, 2022e) with the population of Ontario (Statistics Canada - Statisque Canada, 2022c). The phosphorus contained in each type of imported and exported food is estimated multiplying the amount of ech type of traded food by its phosphorus content (Health Canada, 202).

2.3.2. Industrial sector

Phosphorus flows through imports, production, exports and waste for the steel, forestry, and food and beverage, industries of Ontario were mapped. The steel industry is the first non-food sector in terms of phosphorus use. The main phosphorus inflows of steel manufacturing are associated with the use of iron ore, coal, and coke, while the main outflow of phosphorus is within slag, which remove most of the impurities from steel, including phosphorus. It must be noted that, although some minor amounts of phophosphorus can be desired in steel for making anti-corrosion surface coatings, it is largely considered an impurity in the steel manufacturing process. Phosphorus in these flows is estimated multiplyting their average phosphorus content (0.06% P in iron ore, 0.05% P for coal, 0.4% P in slag, and 0.01% in steel) 176 REF by the steel production capacity of the facilities located in Ontario (Cheminfo Services Inc., 2019; Algoma Steel Inc., 2022; Stelco Inc., 2022; Pollution Probe, 2022) and the imports and exports of these materials (World Integrated Trade Solution, 2022; Statistics Canada - Statisque Canada, 2022a).

Phosphorus flows in Ontario's forestry industry includes wood harvesting, wood products manufacturing, as well as the production of pulp and paper. The estimation of these phosphorus flows are the result of multiplying the production data of wood, wood products, pulp and paper, and their retrospectives imports, exports, and waste streams (Canadian Forest Service, 2020; Statistics Canada - Statisque Canada, 2022a), by the average phosphorus content, which is assumed to be 0.01% for wood 181 REF and 0.005% for pulp and paper products REF.

Phosphorus in aquaculture are mainly due to supply of feed as part of fish feed the grow of trouts, part of which is uptake by fishes, while the rest of phosphorus is released into aquatic ecosystems since aquaculture effluents are directly discharged to the environment (Ontario Ministry of the Environment, Conservation and Parks, 2019). The amount phosphorus uptakes by fishes is calculated multiplying the fish production (Statistics Canada - Statisque Canada, 2021), by their phosphorus content (Health Canada, 202), while the phosphorus content in the aquaculture waste effluents of Ontario is estimated to be 10 kg of phosphorus per ton of fish produced (Bureau et al., 2003). The sum of phosphorus uptakes by fishes and phosphorus in aquaculture waste effluents result in the phosphorus supplied to aquaculture as fish feed.

Regarding other industrial activities which could involve the use of phosphorus, the local production of phosphorus is assumed to be negligible since phosphorus is not mined or refined in Ontario, and the synthetic phosphorus fertilizer imports are accounted in the agricultural section. The general chemical facilities located in Ontario report 350 t/year of phosphorus as waste REF, in addition of imports and exports of chemical products REF. However, there exist a significant fraction of phosphorus used in the industrial sector that cannot be tracked due to the lack of data.

Ask sidney what to do with food industry, and pet feed. My approach is to merge all of them as it is currently in the figure, but confirm with her

2.3.3. Urban sector

In this section we include the phosphorus inflows and outflows through wastewater treatment plants (WWTPs), septic systems, and food and organic waste management facilities (landfills, composting sites, and anaerobic digestion facilities).

Jorge do you mind if the purposes of the papaer we stick with just one method? I think it is better, otherwise it becomes lengthy and confusing

Phosphorus flows through WWTPs is estimated combining data from the National Pollutant Release Inventory (NPRI) REF, a public database of releases, disposals and transfers of pollutants, including industrial facilities, and data from the Wastewater Systems Effluent Regulations (WSER) database REF. Since the NPRI only contains data of those facilities that meet certain regulatory requirements, the information of this database must be complemented with the data from the WSER database, which includes information of Canadian WWTPs at the federal, provincial, and municipal level. The estimations on phosphorus flows through WWTPs are valitaed using the Municipal Treated Wastewater Effluent (MTWE) database REF, which collects annual data on water quality data and effluent levels for WWTPs in Ontario. We note that this data set only provides information about phosphorus releases from municipal WWTPs, but it does not collect phosphorus disposals and transfers. REVISAR POR JORGE. This methodology is shown in Figure 1

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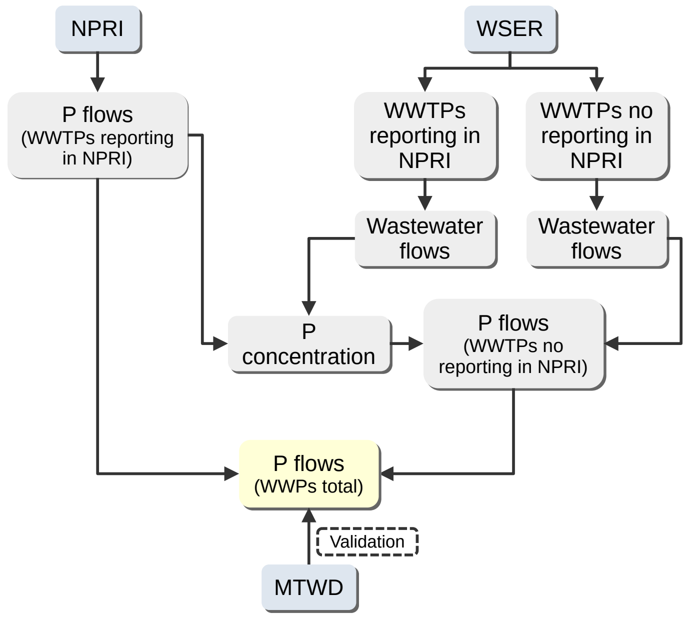

Figure 1: Procedure for estimating phosphorus flows through wastewater treatment plants.

However, there exist households that are not connected to any sewer systems. These households are equipped with septic systems to perform a rough treatment of the wastewater produced prior to its release into the environment, which typically consist into a septic tank that separates solid matter from the wastewater, and a drainfield where the effluent is discharged. The estimation of phosphorus releases from septic systems is based on the fraction of households equipped with these systems, estimated on 13% (Statistics Canada - Statisque Canada, 2015), which are inhabited by an average of 2.58 individuals (Statistics Canada - Statisque Canada, 2017), and the average phosphorus load rate from septic systems, which is estimated on 0.81 kg of phosphor per person per year for the Lake Erie Basin in Ontario by Oldfield et al. (2020).

Phosphorus flows in the form of food and organic waste are based on applying food loss factors for the steps associated with food processing (FAO, 2011), considering the food production and import values estimated in Section 2.3.1.

2.4. *Phosphorus recovery techniques*

There currently exist different processes for phosphorus recovery from different sources which technical viability has been proven or is at advanced development stage, i.e., systems with technologies readiness level (TRL) (National Aeronautics and Space Administration, 2022) of 6 or above (commercial or pilot plant stage). Since the flows from different processes have different properties, the techniques for phosphorus recovery vary between sectors and flows and, therefore, their recovery efficiencies, costs, and products obtained. Table 1 shows a summary of the specifications of the phosphorus recovery technologies for different flows, including literature references where comprehensive descriptions of each system and its specifications can be found. We noted that the phosphorus recovery processes currently available exceed the systems included in this work, nonetheless the processes considered in this study are a selection of the main techniques for phosphorus recovery, although different processes may have been developed on the foundations of the same technique, e.g., the multiple processes based on struvite precipitation.

Phosphorus recovery costs include operating and annualized capital costs. Capital costs are annualized through the application of an annual capital charge ratio ($ACCR$) as defined by Towler and Sinnott (2013), assuming a typical interest rate of 5% and a plant lifetime of 20 years. Dynamic phosphorus recovery costs in function of the processing capacity have been considered in order to capture the economies of scale for those technologies for which sufficient data are available.

In general terms, the process for phosphorus recovery and recycling can be classified into those employed for the treatment of liquid streams, which are based on the formation of precipitated through the direct processing of the liquid effluent, and those processes employed for the treatment of solid fractions, which usually require the pretreatment of the waste through an incineration stage.

Phosphorus in manure represent an important flow within the agricultural sector. The techniques used for phosphorus recovery from cattle and swine manure differ for the liquid and solid fractions. Struvite precipitation is he dominant technology for phosphorus recovery from liquid manure, existing different processes for struvite production based on the type of reactors used with similar recovery efficiencies but different treatment capacities, and thus different recovery costs REF REF REF. Additionally, there exist modular processes based on physical separations oriented to small-scale intensive livestock facilities REF. The recovery of phosphorus from the solid fraction of manure involves the incineration of the waste, and the further processing of the ashes, recovering phosphorus precipitates or phosphoric acid REF REF. Phosphorus recovery from poultry litter is based on acid extraction and further precipitation (Szögi et al., 2008).

Slaughterhouse waste is flow from food industry which can be targeted for phosphorus recovery. It should be noted that slaughterhouse is comprised by a liquid (slaughterhouse wastewater) and a solid fraction (animal carcass waste) and, therefore, the phosphorus recovery systems for each flow will differ. Similarly to the case of phosphorus recovery from manure, phosphorus recovery from slaughterhouse wastewater is performed through through struvite precipitation (AMPC, 2018), while the animal animal carcass waste is incinerated and phosphorus is recovered from ashes in form of calcium carbonate or phosphoric acid (Jupp et al., 2021).

Municipal wastewater contains significant amounts of phosphorus that can be recovered. It must be noted that phosphorus outflows from WWTPs are divided into phosphporus contained in the treated water and phosphorus contained in sludge. Phosphorus contained in water can be recovered through the formation of precipitates such as struvite, while phosphorus contained in sludge can be recovered either through the direct processing of sludge producing precipitates, of from sludge ashes after an incineraiton stage, obtaining different products such as phosphoric acid or calcium phosphare.

3. Results and discussion

3.1. Phosphorus flows in Ontario

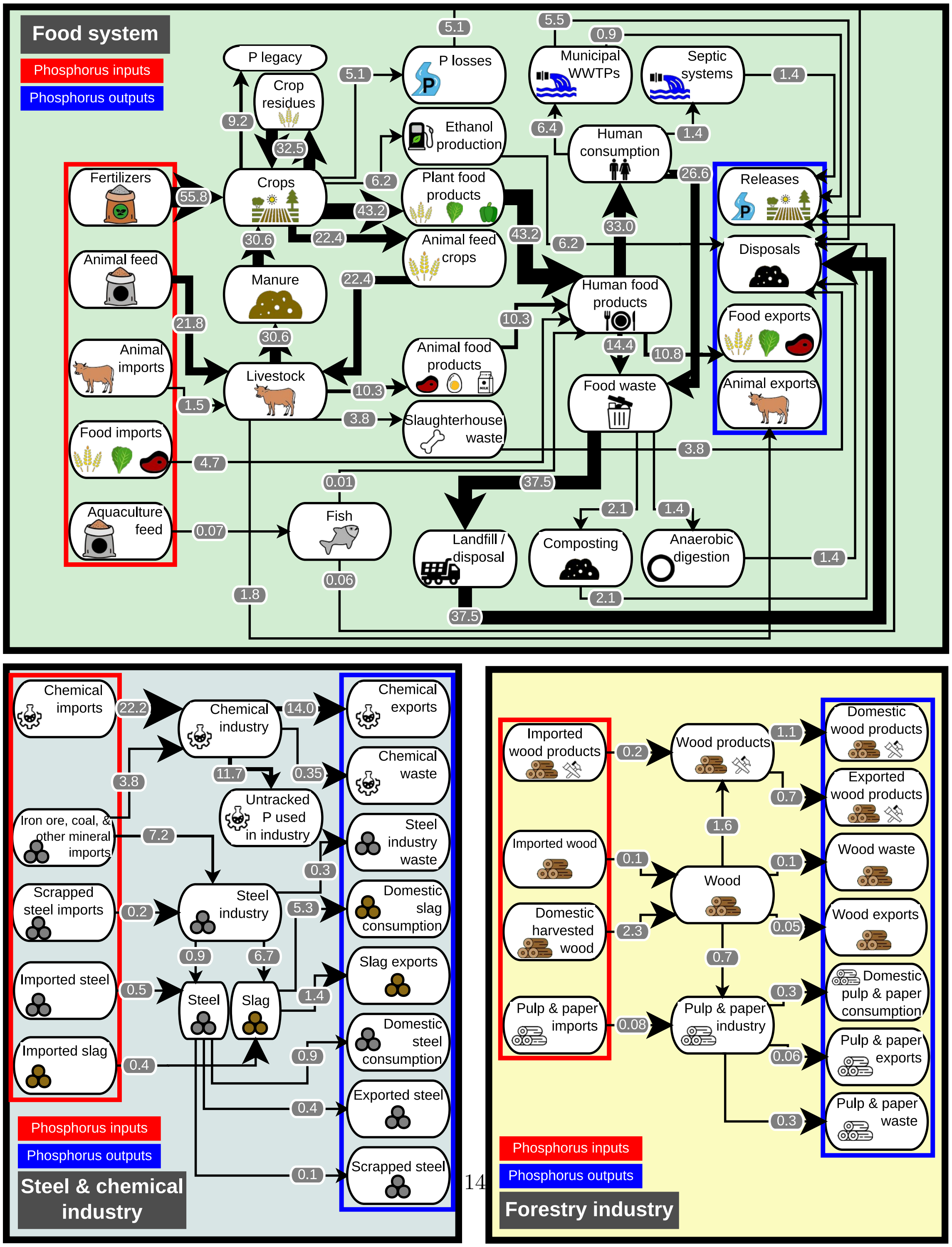

Figure 2: Phosphorus flows in the province of Ontario (kt/year). The streams within red rectangles denote phosphorus inflows into the province, while those streams within blue rectangles denote phosphorus outflows out of the province.

Figure 2 summarizes the phosphorus flows in the province of Ontario. It can be observed that phosphorus flows in anthropogenic activities can be divided into 3 independent networks, i.e., the flow of phosphorus involved the production and processing of food (including the treatment of wastewater), the flow of phosphorus used in the steel and chemical industries, and the phosphorus involved in the forestry industry.

The main inflows food production and processing network are those associated with the supply of synthetic fertilizers and livestock feed, accounting for 55.6 and 21.8 kt/year respectively. Other phosphorus imports in Ontario are made in the form of food products (4.7 kt/year) and aquaculture feed imports (0.07 kt/year). Crop residues and manure are the main phosphorus waste effluent from the agricultural sector, accounting for 32.5 and 30.6 kt/year. However, it must be notted the differente properties of these materials. While crop residues can be left in the cropfields, transfering part of the phosphorus taken by crops back to soil and acting as soil amendment materials due to their carbon content REF, manure produced in intensive livestock facilities is a point source of phosphorus releases highly spatially concentrated, resulting in the accumulation of phosphorus in the vicinity of these facilities. As a consequence, the production of manure has the potential of being environmentally harmful and requires of adequate management strategies. The food processing industry involves the largest flows within the province, which can be classified plant and animal-based product, and slaughter house waste, resulting in phosphorus flows of 43.2, 10.3, and 3.8 kt/year respectively. A significant fraction of end-flows are waste flows in the form of landfill (37.5 kt/year), composting (2.1 kt/year), and anaerobic digestion (1.4 kt/year) disposals, as well as wastewater (7.8 kt/year). Phosphorus exports out of Ontario are performed through the exports of food products and livestock, accounting for 10.8 and 1.8 kt/year respectively.

Chemical industry involve significant phosphjorus flows, importing 22.2 kt/year into the province, while the exports represent 14.0 kt/year. This sector produces 0.35 kt/year of phosphorus that is classified as waste. However, an important fraction of phosphorus used by this sector (11.7 kt/ton) cannot be tracked and. therefore, it is unknown what fraction of this phopshorus can result as waste. Steel production imports 8.3 kt/year of phosphorus, of which 7.0 kt/year ends as steel wast or slag, while the phosphorus flows in steel materials are 1.4 kt/year.

Phosphorus imports from the forestry industry are 0.38 kt/year, while 2.3 kton/year of phosphorus is taken from wood harvested in Ontario. This sector releases 0.4 kton/year of phosphorus in the form of wood and pulp waste, while 0.81 kt/year of phosphorus is exported out of the province as wood, wood products or pulp and paper.

3.2. Potential of phosphorus recovery in Ontario

The potential for phosphorus recovery in the province of Ontario through the deployment of different processes for the recovery of phosphorus from different flows is assess in this section. As shown in Section 2.4, different processes can be employed for the recovery of phosphorus from the same stream. However, each system is design for operating under certain conditions and they have different processing capacities. As a result, phosphorus recovery efficiency and cost will differ between technologies for the treatment of the same flow. In order to explore this variability between phosphorus recovery systems, all the systems described in Table 1 are evaluated. The results obtained in terms of phosphorus recovered and recovery cost for each technology and flow are collected in the Supplementary Material. Two scenarios are selected for deeper analysis, the minimum cost scenario that selects the most economical technology, and the maximum recovery scenario, comprised by the phosphorus recovery system which deployment result in the largest phosphorus recovery.

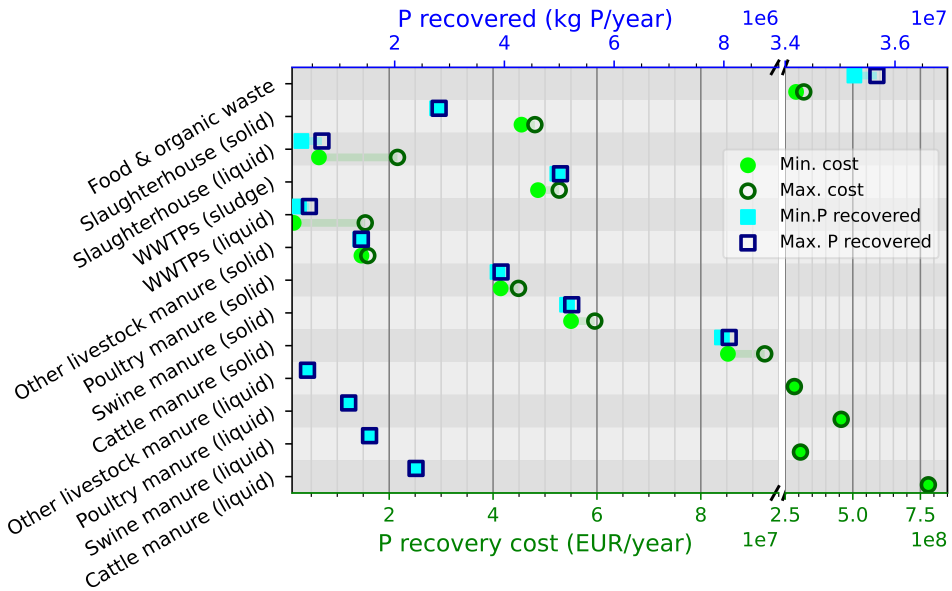

Figure 3: Phosphorus recovered and phosphorus recovery cost in the province of Ontario by flow. Note that the scale of bottom x-axis is different for left and right axes.

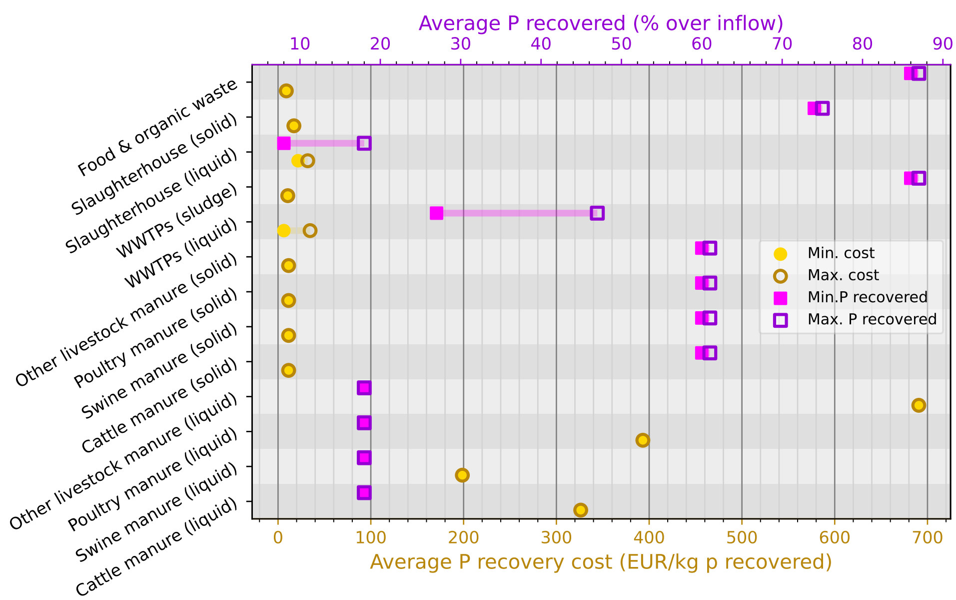

Figure 4: Average phosphorus recovered and average phosphorus recovery cost per kilogram of phosphorus recovered in the province of Ontario by flow.

3.2.1. Agricultural sector

Manure is an agricultural flow from which effective phosphorus recovery might be achieved since it can be collected from the intensive livestock facilities and further treated (Schoumans et al., 2010). The inventory of cattle, swine, poultry, and other livestock for Ontario in 2019 is 1,376,984, 506,768, 148,508, and 135,725 animal units respectively, resulting in the release of 13,274, 8,569, 6,457, and 2,283 metric tonnes of phosphorus per year through manure respectively. Phosphorus recovery from manure is highly influenced by the economies of scale and, therefore, by the scale of the CAFOs (Martín-Hernández et al., 2021). Since no data on the size distribution of CAFOs in Ontario is available, the average sizes of livestock facilities reported by Statistics Canada - Statisque Canada (2022b) for the year 2019 are considered, resulting in average sizes for cattle, swine, pultry and other livestock (primarily sheep and lambs) facilities of 98, 168, 15 and 16 animal units respectively. The number of cattle, swine, poultry, and other livestock CAFOs obtained is 14,051, 3,022, 10,069, and 8,636 respectively, which is in alignment with the number of livestock facilities reported by Statistics Canada - Statisque Canada (2022d).

Phosphorus is divided between the liquid and solid fractions of manure, being the solid fraction the one containing the largest amount of phosphorus, and thus the fraction from which larger quantities amounts of phosphorus can be recovered with lower costs, as observed in Figure 3. However, it must be noted that phosphorus recovery from solid manure involved more complex processes that include the incineration of the waste, which in turn makes the process more energy intensive and may result in environmentally harmful emissions of gases. Cattle manure contains the larges amount of phosphorus as a consequence of being the largest manure flow, followed by swine and poultry manure. However, the comparison of the average phosphorus recovery costs per kilogram of phosphorus recovered shows that phosphorus recovery from swine liquid manure is lowest, as shown in Figure 4. This is due to the size of the swine intensive facilities, which in average are comprised by a larger number of animal units that cattle intensive facilities. This reveals the important role of the economies of scale in phosphorus recovery. Moreover, the small size of the CAFOs in Ontario result in high phosphorus recovery costs, whose values range between 200 and 700 EUR/kg P recovered. These costs are significantly higher than the phosphorus recovery costs reported by Martín-Hernández et al. (2022) for the comparatively larger CAFOs of the U.S. states in the Great Lakes area, which average sizes range from 630 and 2,600 animal units, resulting in phosphorus recovery costs between 13 and 73 USD/kilogram of phosphorus recovered. The phosphorus recovery efficiency is similar for all livestock types since all the process selected is the modular physical separation system due to the small scale of the livestock facilities in Ontario. For the case of solid manure it can be observed that all livestock types show a similar average phosphorus recovery cost as a result of the lack of data to stimate the effect of the economies of scale of these processes.

3.2.2. Industrial and urban sector

Industrial and urban sectors are grouped since some flows belong to both sectors, particularly those related with wastewater, and the organic fraction of industrial and municipal solid waste, including food waste.

Slaughterhouse waste is an industrial flow from which phosphorus can be effectively recovered (AMPC, 2018). Data on individual capacities for the slaughterhouses in Ontario is not available for estimating the effects of the economies of scale on the cost of phosphorus recovery and, therefore, average slaughterhouse capacities are considered, which values are 104,017, 802,186, and $14.4 \cdot 10^6$ cattle, hog, and poultry heads slaughtered/(facility $\cdot$ year) respectively (Agriculture and Agri-Food Canada, 2021a; INAC Services, 2014). Considering the inventory of slaughtered animals reported by Agriculture and Agri-Food Canada (2021c,b), 7, 6, and 17 cattle, hog, and poultry slaughtering facilities are obtained, with associated phosphorus flows of 317.4, 103.5, and 53.2 metric tonnes/(facility $\cdot$ year) respectively. Phosphorus flows from sheep and rabbit slaughtered are considered negligible due to the low number of animals slaughtered. Figure 3 shows that most of phosphorus can be recovered from the solid fraction of waste due to its larger phosphorus content. The variations between the minimum cost and maximum recovery scenarios are not significant for the solid slaughterhouse waste flow, however, for the liquid fraction the phosphorus recovery the difference between these two scenarios increase by a factor of 2.3, while the total recovery cost in the maximum recovery scenario increases by a factor of 3.3 times larger, as shown in Figure 4, showing that the increase of phosphorus recovery efficiency results in a non-linear increase in the phosphorus recovery cost. The numerical results are collected in the Supplementary Material ?

Wastewater is a large flow containing significant amounts of phosphorus. Wastewater is colledted and directed to wastewater treatment plants (WWTPs). These facilities produces a liquid water effluent with adequate environmental parameters for its being releas into the environment, and a sludge flow from the primary and second treatments. Phosphorus can be recovered from both flows, although most of the phosphorus is contained in the sludge fraction. The distribution of phosphorus between treated water and sludge considered is 14.1% - 85.9% respectively (Pollution Probe, 2022), based on the data reproted by NPRI and WSER databases REFs, which is in alignment with the distribution values reported by (Egle et al., 2016). The capacity of the wastewater treatment plants installed in Ontario, together with their phosphorus flows, have been considered to determine the effect of the economies of scale in the cost of phosphorus recovery. Data on Ontario wastewater treament plants capacity and phosphorus releases is collected in the Supplementary Material *Jorge and Roy, would you agree with including this data as part of the Suplementary Material?*. Figure 3 shows that the potential for phosphorus recovery from sludge is greater than from the WWTPs liquid fraction, as mentioned before. Little variation is observed between the minum cost and maximum recovery scenarios for the recovery of phosphorus from sledge, which implies that there exist a certain degree of homogeneity in the current technologies for phosphorus recovery from sludge, which can be appreciated in Figure 4. It must be noted that the phosphorus recovery systems from sludge ashes reveal to be more effective, including the incineration cost, than the direct recovery of phosphorus from sludge due to the higher recovery efficiency of the former ones. Conversely, the phosphorus recovery from the liquid wastewater fraction show a larger variability between both scenarios considered. The phosphorus recovered in the maximum recovery scenario is 1.7 times larger than in the minimum cost scenarios. However, this increase in the phosphorus recovery efficiency result in the increase of the recovery cost by a factor of 9.6, showing that similarly to the case of the liquid fraction of slaughterhouse waste, the achievement of greater recovery efficiencies through the use of more effective technologies result in an exponential increase of recovery costs.

Figure 3 shows that the food and organic waste represent the largest potential for phosphorus recovery. However, it must be noted that this flow includes all those streams comprised by solid organic wastes other than slaughterhouse waste, including food processing industry waste, household food waste, and other municipal organic waste. Similarly to other solid fractions, the minimum cost and maximum recovery scenario shows a narrrow variability regarding phosphorus recovered and recovery costs.

Finally, there are some processes under development for the recovery of phosphorus from steel production industry, particularly from steelmaking slag. These processes are based on selective leaching and further chemical precipitation to obtain solid phosphates (Du et al., 2022, 2019) or magnetic-aid calcium phosphate precipitation (Yokoyama et al., 2007). Although these are promising processes that can result in an effective recovery of phosphorus which can be further recycled, they are at early development stages and, thus, they have not been considered in this assessment.

3.3. Economic implications of phosphorus recovery in Ontario

The scope of this study is oriented to the recycling of the phosphorus recovered and, therefore, the processes studied are those recovering phosphorus in an adequate for being further reused. The comparison between the phosphorus imported for the production of food within Ontario, i.e., in the form of fertilizer or animal feed, and the phosphorus that could be recovered is a useful metric to determine the effectiveness of phosphorus recovery, and the potential reduction of phosphorus supplies from external sources. This assessment is limited to the food production sector shown in Figure 2 since the recovery of phosphorus is performed in different flows belonging to this sector.

3.4. Implications on food sovereignty of phosphorus recovery in Ontario

Implications on food production self-sufficiency derived from the (partial) recycling of P. Discussion on the improvement of the food production system resiliency against disruptions of the global supply supply chains (e.g., current context derived from the COVID-19 pandemia and the war in Ukraine)

3.5. Gaps of knowledge

Further research in phosphorus recovery systems oriented to small scale livestock facilities

4. Conclusions

5. Acknowledgments

Pollution Probe

ECCC

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Table 1: ADD F denotes the phosphorus recovered as $^{\text{kg P}_{\text{recovered}}}/_{\text{year}}$, while $\lceil x \rceil$ represent the ceiling function applied to x. The definition of annual capital charge ratio ($ACCR$) can be found in the Supplementary Material, Section ??.

Sector	Inflow	Pretreatment	Pretreatment cost (EUR/kg $P_{recovered}$)	Technology	Type	P recovery potential (% related to inflow)	P recovery cost (EUR/kg P recovered)	TRL	Ref tech
Agriculture	Cattle and swine manure, liquid phase (30% of total manure P)	Solid-liquid separation (screw press)	See [1]	Multiform	Struvite	60	$25.7 + 1.10 \cdot 10^6 \cdot \lceil 1.19 \cdot 10^{-4} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation (screw press)	See [1]	Crystalactor	Struvite/ Calcium phosphate	60	$3.53 + \left(2.30 \cdot 10^6 + 0.71 \cdot \lceil 3.32 \cdot 10^{-5} \cdot F \rceil\right) \lceil 3.32 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation (screw press)	See [1]	Ostara Pearl 500	Struvite	60	$12.57 + 2.30 \cdot 10^6 \cdot \lceil 7.02 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation (screw press)	See [1]	Ostara Pearl 2K	Struvite	60	$12.57 + 3.10 \cdot 10^6 \cdot \lceil 1.83 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation (screw press)	See [1]	Ostara Pearl 10K	Struvite	60	$12.57 + 10.00 \cdot 10^6 \cdot \lceil 3.65 \cdot 10^{-6} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation (screw press)	See [1]	Nuresys	Struvite	60	$10.37 + 1.38 \cdot 10^6 \cdot \lceil 2.24 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation (screw press)	See [1]	MAPHEX	Solid	90	$184.67 + 0.30 \cdot 10^6 \cdot \lceil 2.47 \cdot 10^{-4} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	6	[1]
	Cattle and swine manure, solid phase (70% of total manure P)	Incineration	8.9	EcoPhos	Phosphoric acid	82	4.5	6	[2,3,4]
		Incineration	8.9	AshDec depollution	Calcium phosphate	86	1.8	6	[2,3,4]
		Incineration	8.9	AshDec Rhenania	Calcium phosphate	86	1.9	6	[2,3,4]
		Incineration	8.9	PASCH	Calcium phosphate	79	4.7	6	[2,3,4]
		Incineration	8.9	LEACHPHOS	Calcium phosphate	78	5.1	9	[2,3,4]
		Incineration	8.9	RecoPhos	Mineral	87	2.5	9	[2,3,4]
		Incineration	8.9	Thermophos	P4	81	2.7	9	[2,3,4]
	Poultry litter	-	-	Quick wash	Solid precipitate	70	4.4	3	[5]
	Slaughterhouse waste, liquid phase (14% of total slaughterhouse P)	-	-	Multiform	Struvite	84	$22.6 + 1.10 \cdot 10^6 \cdot \lceil 1.05 \cdot 10^{-4} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		-	-	Ostara Pearl 500	Struvite	58	$15.60 + 2.30 \cdot 10^6 \cdot \lceil 8.70 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		-	-	Ostara Pearl 2K	Struvite	58	$15.60 + 3.10 \cdot 10^6 \cdot \lceil 2.26 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		-	-	Ostara Pearl 10K	Struvite	58	$15.60 + 10.00 \cdot 10^6 \cdot \lceil 4.53 \cdot 10^{-6} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[6]
	Slaughterhouse waste, solid phase (86% of total slaughterhouse P)	Incineration	14.6	EcoPhos	Phosphoric acid	82	4.5	6	[2,3,7]
		Incineration	14.6	AshDec depollution	Calcium phosphate	86	1.8	6	[2,3,7]
		Incineration	14.6	AshDec Rhenania	Calcium phosphate	86	1.9	6	[2,3,7]
		Incineration	14.6	PASCH	Calcium phosphate	79	4.7	6	[2,3,7]
		Incineration	14.6	LEACHPHOS	Calcium phosphate	78	5.1	9	[2,3,7]
		Incineration	14.6	RecoPhos	Mineral	87	2.5	9	[2,3,7]
		Incineration	14.6	Thermophos	P4	81	2.7	9	[2,3,7]
Urban & industrial	WWTPs (liquid phase)	-	-	Crystalactor	Struvite/ Calcium phosphate	38	$305,920 \cdot \left(\frac{F}{24{,}966}\right)^{0.59} \cdot \frac{1}{F}$	9	[3]
		-	-	Ostara Pearl	Struvite	20	$130,856 \cdot \left(\frac{F}{13{,}140}\right)^{0.36} \cdot \frac{1}{F}$	9	[3]
		-	-	P-RoC	Calcium phosphate	27	$75,970 \cdot \left(\frac{F}{17{,}739}\right)^{0.78} \cdot \frac{1}{F}$	6	[3]
		-	-	REM-NUT	Struvite	47	$977,933 \cdot \left(\frac{F}{30{,}879}\right)^{0.94} \cdot \frac{1}{F}$	6	[3]
		-	-	AirPrex	Struvite	15	$74,195 \cdot \left(\frac{F}{9{,}855}\right)^{0.38} \cdot \frac{1}{F}$	9	[3]
		-	-	PRISA	Struvite	18	$186,923 \cdot \left(\frac{F}{11{,}826}\right)^{0.43} \cdot \frac{1}{F}$	6	[3]
	WWTPs (sewage sludge, 60-90% of P)	-	-	Stuttgart process	Struvite	40	$581,730 \cdot \left(\frac{F}{26{,}280}\right)^{0.89} \cdot \frac{1}{F}$	9	[3]
		-	-	Gifhorn process	Struvite	40	$400,384 \cdot \left(\frac{F}{26{,}280}\right)^{0.82} \cdot \frac{1}{F}$	9	[3]
		-	-	PHOXNAN	Struvite	51	$891,667 \cdot \left(\frac{F}{33{,}507}\right)^{0.84} \cdot \frac{1}{F}$	6	[3]
		-	-	Aqua Reci	Calcium phosphate	61	$939,605 \cdot \left(\frac{F}{40{,}077}\right)^{0.82} \cdot \frac{1}{F}$	6	[3]
		-	-	MEPHREC	P rich slag	68	$1,154,473 \cdot \left(\frac{F}{44{,}676}\right)^{0.61} \cdot \frac{1}{F}$	6	[3]
	WWTPs (sewage sludge ash SSA, 60-90% of P)	Incineration	8	EcoPhos	Phosphoric acid	82	4.5	6	[3]
		Incineration	8	AshDec depollution	Calcium phosphate	86	1.8	6	[3]
		Incineration	8	AshDec Rhenania	Calcium phosphate	86	1.9	6	[3]
		Incineration	8	PASCH	Calcium phosphate	79	4.7	6	[3]
		Incineration	8	LEACHPHOS	Calcium phosphate	78	5.1	9	[3]
		Incineration	8	RecoPhos	Mineral	87	2.5	9	[3]
		Incineration	8	Thermophos	P4	81	2.7	9	[3]
	Organic municipal & food waste	-	-	Chemical extraction and Struvite precipitation	Struvite	94	24.8	3	[8]
		Incineration	6.43	EcoPhos	Phosphoric acid	82	4.5	6	[3,9,10]
		Incineration	6.43	AshDec depollution	Calcium phosphate	86	1.8	6	[3,9,10]
		Incineration	6.43	AshDec Rhenania	Calcium phosphate	86	1.9	6	[3,9,10]
		Incineration	6.43	PASCH	Calcium phosphate	79	4.7	6	[3,9,10]
		Incineration	6.43	LEACHPHOS	Calcium phosphate	78	5.1	9	[3,9,10]
		Incineration	6.43	RecoPhos	Mineral	87	2.5	9	[3,9,10]
		Incineration	6.43	Thermophos	P4	81	2.7	9	[3,9,10]

1: Martín-Hernández et al. (2021)
2: Jupp et al. (2021)
3: Egle et al. (2016)
4: Schoumans et al. (2010)
5: Szögi et al. (2008)
6: AMPC (2018)
7: Zagklis et al. (2020)
8: Fernández-Delgado et al. (2022)
9: Ohtake and Tsuneda (2019)
10: Sharma and Chandel (2021)