Mapping of phosphorus flows and analysis of the potential for recovery and reuse in Ontario, Canada

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Abstract

Phosphorus is a key non-renewable element used in multiple economic activities, and notably for food production. However, sustained releases over time have led to nutrient pollution and eutrophication of ecosystems. This paper maps the phosphorus flows through Ontario's economic sectors and identifies potential opportunities for phosphorus recovery and recycling. Phosphorus flows associated with food production and processing, including wastewater and food waste are the main targets. Up to 86% of phosphorus imports for food production could be covered by recycled phosphorus, with an average recovery cost of 36 EUR/kg of phosphorus. This cost is lower than the estimated economic losses caused by the release of a kilogram of phosphorus into the environment, but is significantly higher than the per kg cost of fossil-based commercial phosphorus products. Additionally, phosphorus recovery costs vary widely for different waste streams, suggesting the need of exploring cooperative approaches for effective phosphorus recovery at regional scale.

Keywords: Phosphorus recovery, Circular economy, Nutrient pollution, Eutrophication, Food sovereignty

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1. Introduction

Phosphorus is an essential element for the production of food. It has been intensively used for crop and livestock production since the development of synthetic fertilizers and feed supplements

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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 (Reid and Schneider, 2019), while the run of intensive livestock operations, result in important difficulties in the management of the large amounts of manure produced. This is often spread on lands in the vicinity of the livestock operations, which in turn leads to the accumulation of phosphorus in the soil. Although soil acts as a phosphorus reservoir (Ehlert et al., 2003), building-up a legacy P that can be used for future crops, it can also be transported to waterbodies by erosion and runoff, resulting in 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, 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 phosphorus reserves are concentrated in a few number of regions, the supply of phosphorus from a limited number of suppliers lacks resilience and it has been proven that it can be globally disrupted by regional events and conflicts (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 sustainable, reliable, and sovereign food production systems.

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, the mapping of phosphorus flows involved in human activities to detect opportunities for recovery and recycling is essential to determine the fraction of phosphorus which recovery is viable, promoting a circular economy that enhances the sustainability of food production systems in terms of resiliency, savings from the reduction of phosphorus imports, and mitigation of phosphorus pollution. The detailed quantification of phosphorus flows has been addressed in the literature for certain sectors, particularly for the agri-food sector (Boh and Clark, 2020; Zhou et al., 2021; Nesme et al., 2018). In addition, phosphorus flows have also been studied at global (Villalba et al., 2008; Chen and Graedel, 2016) and national scales (Van Dijk et al., 2016; Klinglmair et al., 2015), although these studies tend to aggregate the flows by major sectors, resulting in a lower flow resolution.

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 they do not include quantitative assessments on the amount of phosphorus that is feasible to recover along with the costs involved. Conversely, those works focused on estimating the recoverable phosphorus and the associated recovery costs target specific activities such as livestock production (Martín-Hernández et al., 2021; Sampat et al., 2018) and wastewater treatment (Egle et al., 2016; Nättorp et al., 2017). However, a holistic approach mapping the phosphorus flows and identifying the key streams for phosphorus recovery and reuse is a crucial stage to promote the debate about global and regional circular nutrient economies and redistribution systems (Kahiluoto et al., 2021), and to design important aspects of future phosphorus recycling strategies such as the design of coordinated markets (Sampat et al., 2019) and incentive policies (Martín-Hernández et al., 2022).

In this work, we intend to perform a holistic approach to phosphorus management, recovery, and recycling through the study of 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. These data are 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. Different phosphorus recovery technologies with technology readiness levels equal or above 6 are evaluated, as well as the phosphorus recovery costs of each one of them. Finally, we discuss the impacts that would be derived from implementing active phosphorus recovery and recycling approaches regarding phosphorus supply and use in Ontario.

2. Methods

2.1. Spatial and temporal boundaries

Phosphorus flows have been mapped through a material flow analysis (MFA) (Brunner and Rechberger, 2016) conducted within the political boundaries of the Canadian province of Ontario using data reported for the year 2019.

2.2. Estimation of phosphorus flows

The estimation of phosphorus flows in Ontario's economic sectors is based on the use of open data sources, often from governmental institutions, complemented with information from scientific articles when needed. In the next sections, we describe the general procedure followed to estimate the phosphorus flows of each sector. For a comprehensive description of the procedure followed for estimating each particular phosphorus flow, we refer the reader to the methodology described in Pollution Probe (2022).

2.2.1. Agriculture and aquaculture sector

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

Phosphorus in livestock feeding and manure is estimated based on the number and type of animals reported for Ontario in the Census of Agriculture, including cattle (Statistics Canada – Statistique Canada, 2021a), swine (Statistics Canada – Statistique Canada, 2021e), poultry (Statistics Canada – Statistique Canada, 2021f), and other livestock (Statistics Canada – Statistique Canada, 2021g,d), multiplied by the phosphorus feeding requirements and concentration of phosphorus in manure (Statistics Netherlands, 2012; Brown, Christine, 2013; Van Staden et al., 2021). 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 (Yang et al., 2007).

Phosphorus flows through the imports and exports of animals are estimated using data on animal imports and exports (Statistics Canada – Statistique Canada, 2021b,c,h) multiplied by their phosphorus to live weight ratios (Statistics Netherlands, 2012).

Phosphorus contained in meat and slaughterhouse waste is based on the number of animals slaughtered reported by both federally and provincially licensed meat plants (Agriculture and Agri-Food Canada, 2021c,b) multiplied by the concentration of phosphorus in carcasses (Agriculture and Agri-Food Canada, 2021d; Hayse and Marion, 1973; Brake et al., 1995; Statistics Netherlands, 2012).

Phosphorus flows associated with the production of milk and eggs are based on provincial production data (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2020a,b), multiplying these products by their average phosphorus concentration (Health Canada, 2008; Chambers et al., 2017).

Phosphorus applied to open fields as synthetic fertilizer is estimated based on the amount of fertilizer products traded to Ontario's agricultural markets containing phosphorus (Statistics Canada – Statistique Canada, 2022). Regarding manure, we assume that all of the manure generated by livestock is applied in crop fields (van Bochove et al., 2010).

The uptake of phosphorus by crops is determined based on the area used in each census division (Opendatasoft, 2019) to grow each type of crops by census division (Agriculture and Agri-Food Canada, 2022a,b,c) multiplied by the specific yield and phosphorus content for each crop type (United States Department of Agriculture, 2009). The phosphorus uptake by crops is divided according to whether it is taken up 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 or synthetic fertilizer is lost through erosion, runoff, and drainage. The magnitude of this flow depends on a range of factors, including the amount of phosphorus applied; soil composition, texture, and slope; and precipitations, 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 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) (Zhang et al., 2015; Wang et al., 2018; Tan and Zhang, 2011). In addition, 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 sustained periods of time, often applying phosphorus in greater quantities than crops require to ensure satisfactory yields (Reid et al., 2019). 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 by erosion and runoff).

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 and phosphorus releases from greenhouse irrigation systems also known as greenhouse nutrient feedwater (GNF) systems (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2021). The phosphorus uptake by greenhouse crops is determined by multiplying the production of greenhouse crops (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2022) by the phosphorus content of each vegetable type (United States Department of Agriculture, 2009). The phosphorus releases from the GNF systems were estimated based on the average concentration of phosphorus in GNF outlet streams for Ontario, 33.6 mg/L (Ontario Ministry of the Environment, Conservation and Parks, 2012), and the total water discharges from GNF systems, assuming that the water discharges are equivalent to 25% of the total water applied in greenhouses, which corresponds with the worst-case scenario of no water recirculation in the GNF systems (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2021). The average water consumption in greenhouses in Ontario was assumed to be 1,000 L/m^2/year (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2011). We have also estimated the phosphorus releases from the seasonal workers living 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 (Government of Canada, 2022), and an average phosphorus load rate of 0.0156 kg P/person/week from septic systems (Oldfield et al., 2020).

Phosphorus enters aquaculture systems as fish feed, primarily in the growth of trouts. A fraction of this phosphorus goes to the fish and the remainder is discharged into aquatic ecosystems as aquaculture effluents (Ontario Ministry of the Environment, Conservation and Parks, 2019). The total phosphorus in fish produced in Ontario is calculated by 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 phosphorus in Ontario fish feed that is supplied to aquaculture, is estimated to be the sum of the phosphorus in the fish produced and the phosphorus in aquaculture effluent.

2.2.2. Industrial sector

Phosphorus flows through imports, production, exports and waste for the food, steel, and forestry industries of Ontario were mapped.

Processed food imports and exports 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 by multiplying the amount of each type of traded food by its phosphorus content (Health Canada, 202). Phosphorus flows in the form of food and organic waste are based on applying food loss factors for the steps associated with food processing, from the production of food raw materials to consumption (FAO, 2011), considering the food production and import values estimated in Section 2.2.1.

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, a by-product of steelmaking. During steelmaking, most of the impurities, including phosphorus, separate into the slag phase. It must be noted that, although some minor amounts of phosphorus 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 by multiplying 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) (Yokoyama et al., 2007) 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). The P in slag is estimated using component balancing.

Phosphorus flows in Ontario's forestry industry include 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 respective imports, exports, and waste streams (Canadian Forest Service, 2020; Statistics Canada - Statisque Canada, 2022a), by their average phosphorus content. The average phosphorus content used for wood is 0.01% (Sardans and Peñuelas, 2013) and 0.005% is estimated for pulp and paper products, using component balancing.

The local production of phosphorus is assumed to be negligible since phosphorus is not mined or refined in Ontario. Synthetic phosphorus fertilizer and phosphorus chemical imports are estimated similar to food imports. The phosphorus fertilizer imports are accounted for in the agricultural section. Chemical facilities located in Ontario report 350 t/year of phosphorus as waste (Pollution Probe, 2022). However, a significant fraction of phosphorus used in the industrial sector cannot be tracked due to the lack of data.

2.2.3. 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).

Phosphorus flows through WWTPs are estimated combining data from the National Pollutant Release Inventory (NPRI) (Environment and Climate Change Canada, 2021a), a public database of releases, disposals and transfers of pollutants , and data from the Wastewater Systems Effluent

Regulations (WSER) database (Environment and Climate Change Canada, 2021b). 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 federal, provincial, and municipal levels. The estimations on phosphorus flows through WWTPs are valitaed comparing the data obtained with the information reported by the Municipal Treated Wastewater Effluent (MTWE) database (Ontario Ministry of the Environment, Conservation and Parks, 2021), which collects annual data on water quality 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 flows through sludge disposals. This methodology is shown in Figure 1.

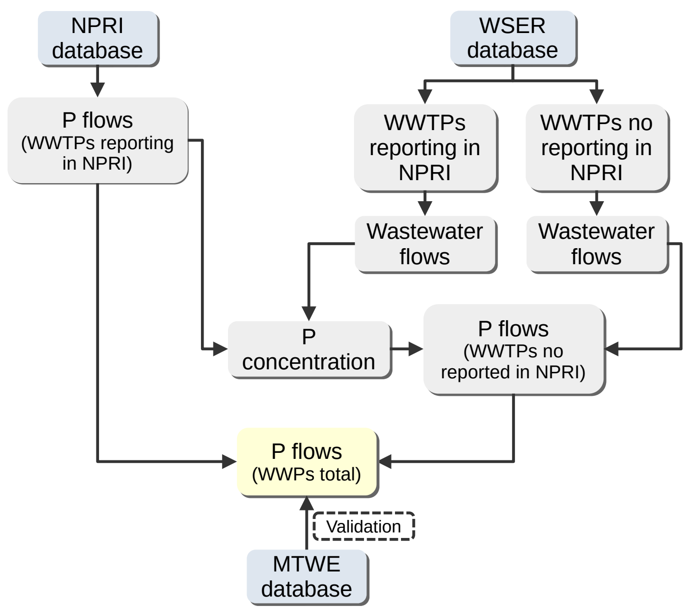

Figure 1: Procedure for estimating phosphorus flows through wastewater treatment plants (MTWE: Municipal Treated Wastewater Effluent, NPRI: National Pollutant Release Inventory, WSER: Wastewater Systems Effluent Regulations, WWTP: Wastewater Treatment Plant).

There exist households that are not connected to any sewer system but they are equipped with septic systems to perform a rough treatment of the wastewater produced prior to its release into the environment. This typically consists of 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 at 13% (Statistics Canada - Statisque Canada, 2015), which are inhabited by an average of 2.58 individuals (Statistics Canada - Statisque Canada, 2017). The average phosphorus load rate from septic systems assumed is 0.81 kg of phosphorus per person per year (Oldfield et al., 2020).

2.3. Phosphorus recovery techniques

There 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 technology 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 are different. Table A.1, which is included in the Appendix, 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 note 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. However, different processes may have been developed on the foundations of the same technique, e.g., the multiple processes are 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 processes for phosphorus recovery and recycling can be classified into those employed for the treatment of liquid streams, which are based on the formation of precipitates through the direct treatment of the liquid effluent, and those processes employed for the treatment of solid fractions, which usually require the pretreatment of the waste, e.g., through an incineration stage.

Phosphorus in manure represents 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 the dominant technology for phosphorus recovery from liquid manure. There exist 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 (Martín-Hernández et al., 2021). Additionally, there exist modular processes based on physical separations oriented to small-scale intensive livestock facilities (Church et al., 2018). 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 (Jupp et al., 2021; Egle et al., 2016). Phosphorus recovery from poultry litter is based on acid extraction and further precipitation (Szögi et al., 2008).

Slaughterhouse waste is a flow from the food processing 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). Similarly to phosphorus recovery from liquid manure, phosphorus recovery from slaughterhouse wastewater is performed through struvite precipitation (AMPC, 2018), while the 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 phosphorus 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 or calcium phosphate, while phosphorus contained in sludge can be recovered either through the direct processing of sludge producing precipitates or from sludge ashes after an incineration stage, obtaining different products such as phosphoric acid or calcium phosphate.

3. Results and discussion

3.1. Phosphorus flows in Ontario

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 in the production and processing of food (including the treatment of organic solid waste and wastewater), the flow of phosphorus used in the steel and chemical industries, and the phosphorus involved in the forestry industry.

The main inflows of the 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 (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, respectively. While crop residues are usually left in the cropfields, transferring part of the phosphorus taken up by crops back to soil and acting as soil amendment materials, manure produced in intensive livestock operations is a spatially concentrated point source of phosphorus releases, resulting in the accumulation of phosphorus in the vicinity of these facilities. As a consequence, the production of manure can result in negative environmental impacts and requires adequate management strategies. The food processing industry involves the largest flows within the province, which can be classified as plant and animal-based food products, and slaughterhouse 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.

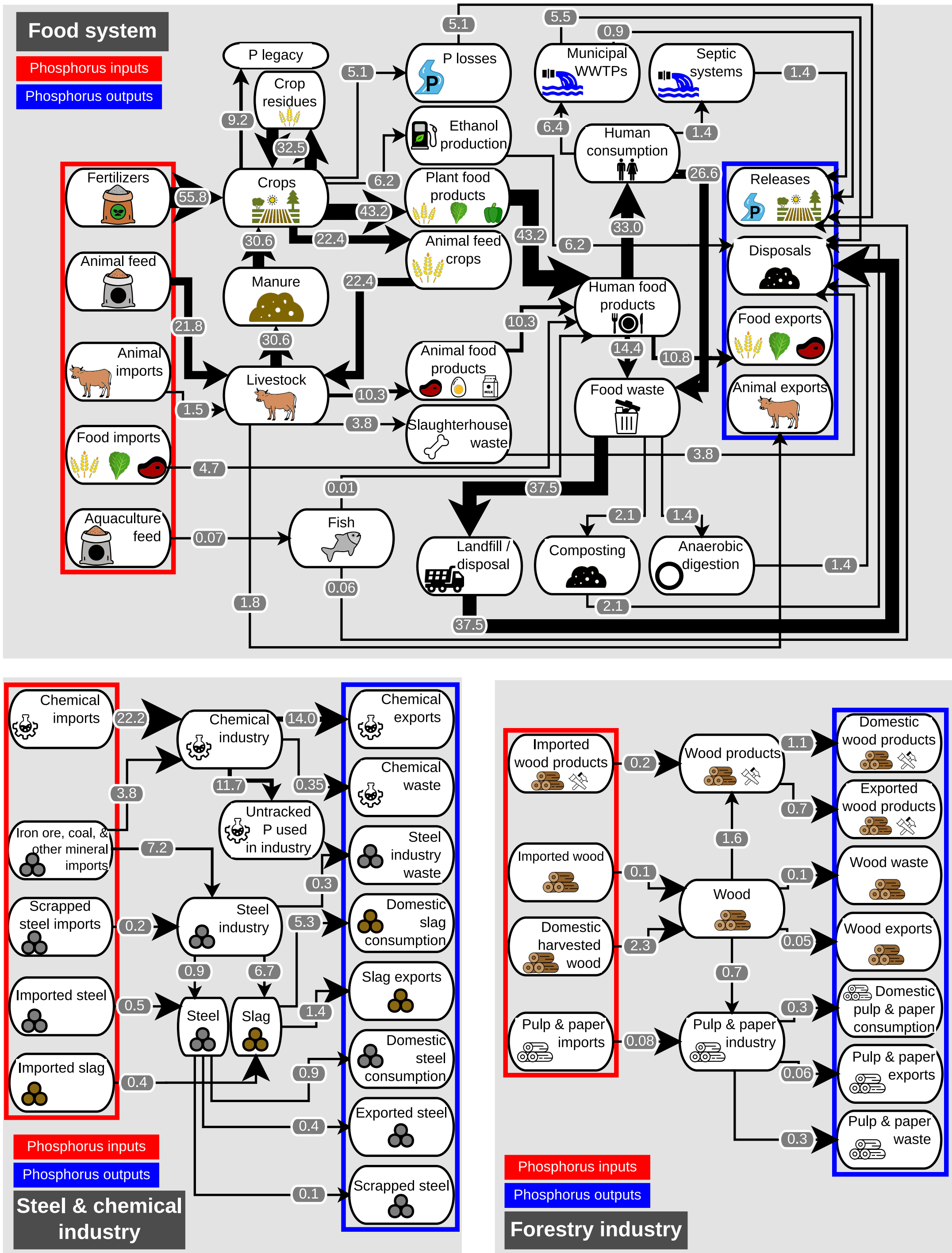

Figure 2: Phosphorus flows in the province of Ontario (kt/year). The streams within red rectangles denote phosphorus inflows into the province, while those streams within blue rectangles denote phosphorus outflows out of the province.

Chemical industry involve significant phosphorus 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 is the real amount of phosphorus disposed as waste. Steel production imports 8.3 kt/year of phosphorus, of which 7.0 kt/year ends as steel waste or slag, while the phosphorus outflows through 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 local wood harvested within 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, manufactured wood products, pulp, and paper.

3.2. Potential of phosphorus recovery in Ontario

The potential for phosphorus recovery in the province of Ontario is assessed in this section. As shown in Section 2.3, different processes can be employed for the recovery of phosphorus from the same stream. However, each system is designed for operating under certain conditions and they have different processing capacities. As a result, phosphorus recovery efficiency and cost may vary 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 A.1 are evaluated. Two scenarios are selected for deeper analysis: the minimum cost scenario, in which the most economical technology is selected, and the maximum recovery scenario, in which the phosphorus recovery processes recovering the largest amount of phosphorus are selected.

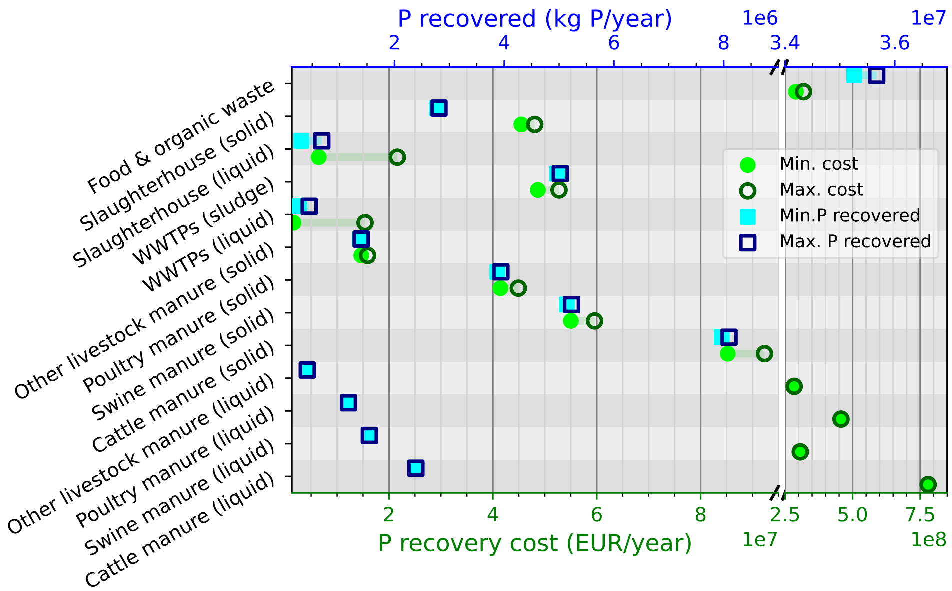

Figure 3: Phosphorus recovered and phosphorus recovery cost in the province of Ontario by flow. Note that the scale of bottom x-axes is different.

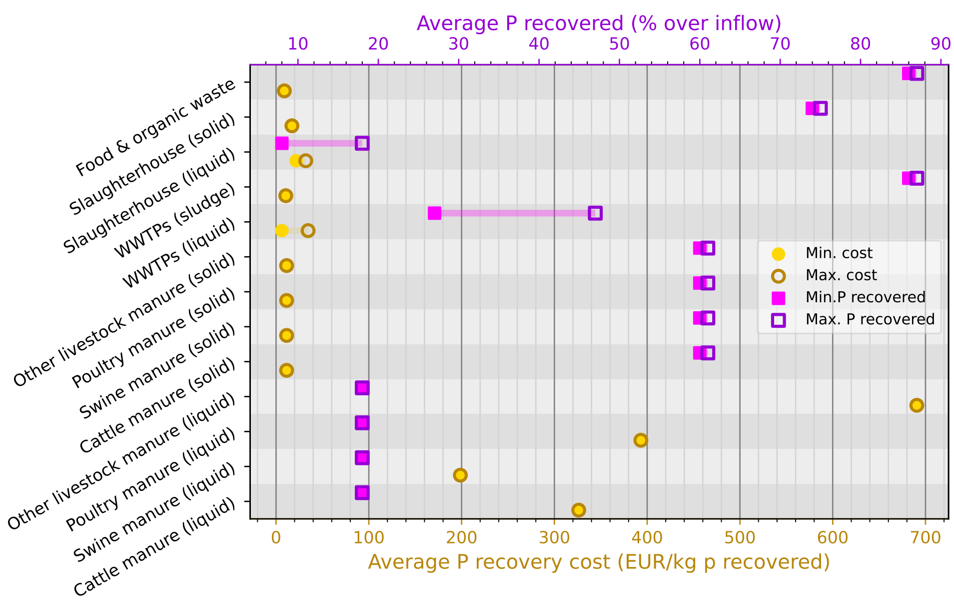

Figure 4: Average phosphorus recovered and average phosphorus recovery cost per kilogram of phosphorus recovered in the province of Ontario by flow.

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 operations and be 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. An animal unit is defined as an animal equivalent of 1,000 pounds (453.6 kg) live weight (U.S. Department of Agriculture, 2011).

Phosphorus recovery from manure is highly influenced by the economies of scale and, therefore, by the scale of the livestock operations (Martín-Hernández et al., 2021). Since no data on the size distribution of livestock operations 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, poultry 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 operations 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 amounts of phosphorus can be recovered at lower costs, as it can be observed in Figure 3. However, it must be noted that phosphorus recovery from solid manure involved more complex processes, since they 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 more cost-effective, 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 than cattle intensive facilities. This reveals the important role of the economies of scale in phosphorus recovery. However, in general terms the small size of the livestock operations in Ontario results 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 livestock operations of the U.S. states in the Great Lakes area, whose average sizes range from 630 to 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 the processes selected are the modular physical separation system MAPHEX (Church et al., 2018) due to the small scale of the livestock facilities. It was not possible to evaluate the effect of the economies of scale for the processes intended to phosphorus recovery from the solid fraction of manure due to the lack of techno-economic data available for them.

3.2.2. Industrial and urban sector

Industrial and urban sectors are grouped since some flows belong to both sectors, particularly those related to 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 to estimate the effect of the economies of scale on the cost of phosphorus recovery. 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 slaughtered sheep and rabbit 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 slaughterhouse wastewater, phosphorus recovery for the maximum recovery scenario increases by a factor of 2.3 over the minimum cost scenario, while the total recovery cost increases by a factor of 3.3, as it can be observed in Figure 4. Therefore, 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 collected and directed to wastewater treatment plants (WWTPs). These facilities produce a liquid water effluent with adequate environmental parameters for being released into the environment, and a sludge flow from the primary and secondary treatments. Phosphorus can be recovered from both flows, although most of the phosphorus is contained in the sludge fraction. The distribution of phosphorus assumed for treated liquid water and sludge is 14.1% and 85.9% respectively, based on the data reported by NPRI and WSER databases (Environment and Climate Change Canada, 2021a,b), 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 analyzed to determine the effect of the economies of scale in the cost of phosphorus recovery. Figure 3 shows that the potential for phosphorus recovery from sludge is greater than from the liquid fraction, as mentioned before. Little variation is observed between the minimum cost and maximum recovery scenarios for the recovery of phosphorus from sludge, which implies that there exists a certain degree of homogeneity in the current technologies for phosphorus recovery from sludge. This can also 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 shows 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 results 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 results 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 waste, household food waste, and other municipal organic waste. Similarly to other solid fractions, the minimum cost and maximum recovery scenarios show a narrow 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

In order to compare the costs derived from the recovery of anthropogenic phosphorus, Figure 5 shows the average phosphorus recovery cost in Ontario along with the long-term social and environmental economical losses derived from uncontrolled releases of phosphorus into the environment estimated by Sampat et al. (2021), and the temporal evolution of prices for different phosphorus commodities reported by the World Bank's Commodity Markets report (The World Bank, 2022), i.e., phosphate rock, diammonium phosphate (DAP), and triple superphosphate (TSP) together. The costs are normalized per mass unit of phosphorus, assuming that the phosphorus content of commercial phosphorus rock ranges from 28 to 34% in mass basis (FAO & IAEA, 2004; Kaiser and Pagliari, 2018), while phosphorus content of DAP and TSP is 20% and 19% respectively. The prices have been adjusted to the year 2020 through the Consumer Price Index (CPI) elaborated by the U.S. Census Bureau (U.S. Census Bureu, 2021).

It can be observed that the average cost of phosphorus recovery in Ontario, valued around 36 EUR/kg of phosphorus recovered, is significantly lower than the economic losses derived from the release of phosphorus into the environment, estimated at 74.5 EUR/kg P in the context of state of Wisconsin, U.S. This provides an economical support to the recovery of phosphorus, since high long-term costs derived from the social and environmental damages caused by phosphorus releases into the environment could be avoided through the recovery of phosphorus from waste streams. Nevertheless, it can be observed that the cost of phosphorus obtained from recovery processes is more costly than phosphorus in commercial fertilizers obtained from mining, which reduces the economic incentives for the recovery and reuse of phosphorus. As a consequence, further support in form of environmental and/or agricultural regulations, phosphorus recovery incentives, or sustainability arguments are needed in order to promote the recovery and recycling of phosphorus.

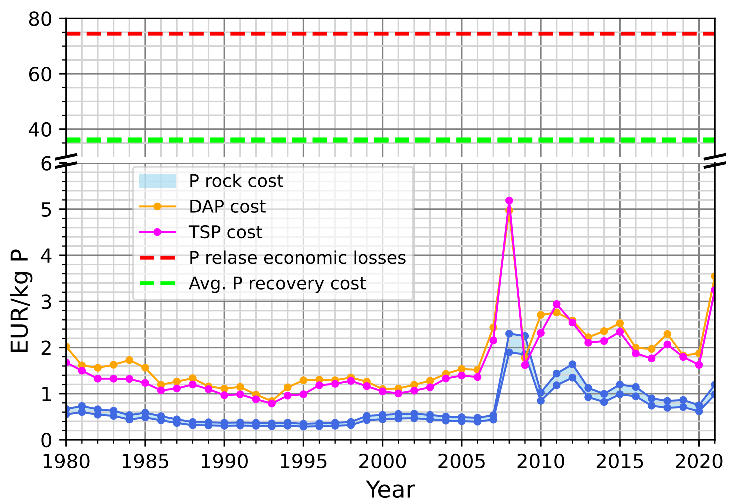

Figure 5: Average phosphorus recovery cost in Ontario, economical losses derived from the releases of phosphorus into the environment (Sampat et al., 2021), and temporal evolution of prices for different phosphorus commodities. Note that the scale of y-axis is different for top and bottom axes.

Additionally, Figure 5 shows that average cost of phosphorus recovery within the province is around 36 EUR/kg of phosphorus recovered, however, in Figure 4 we can observe that phosphorus recovery costs can reach significantly higher values, particularly for the recovery of phosphorus from manure due to the lack of economies of scale of Ontario's livestock operations. Therefore, regional cooperative strategies could be implemented to develop a coordinated action against nutrient pollution, distributing the benefits and costs of phosphorus recovery, and prioritizing the total utility rather than the utility of each stakeholder, similarly to the cooperative approaches proposed for minimizing the cost of reducing greenhouse gases emissions from electricity generation (Galán-Martín et al., 2018).

3.4. Potential for phosphorus recycling in Ontario

Phosphorus recovered can be further recycled within the food production system, developing a circular economy around the use of phosphorus. Phosphorus recovery and recycling would result in curbing the depletion of phosphorus rock reserves and the reduction of the dependency on phosphorus supply from other regions. Considering these factors, there exist some governmental initiatives that, through the creation of different forums and platforms, aim to promote the recovery and recycling of phosphorus (IISD, 2018; Pollution Probe, 2022). In addition, the European Union is setting specific targets to reduce the use of non-renewable materials in fertilizer production (European Comission, 2018) and to promote the use of waste-based fertilizers (European Comission, 2022), encouraging the effective recovery and recycling of phosphorus, and they could serve as a guideline to support phosphorus recovery in other regions.

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, as it is shown in Figure 6, 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 depicted in Figure 2 since the recovery of phosphorus is performed in different flows belonging to this sector.

Figure 6 shows that up to 88% of the phosphorus used for food production, excluding imports of food that have been produced elsewhere, could be recovered and recycled in the best case scenarios where no phosphorus losses occur between the recovery and the reuse stages. However, an effective recycling of phosphorus implies the redistribution of this material from the locations where it is released to to phosphorus-deficient cropfields. It must be considered that the transportation of phosphorus products result in additional costs that can hinder the recycling of phosphorus, as well as environmental impacts related with the current use of fossil fuels-based transportation vehicles. In

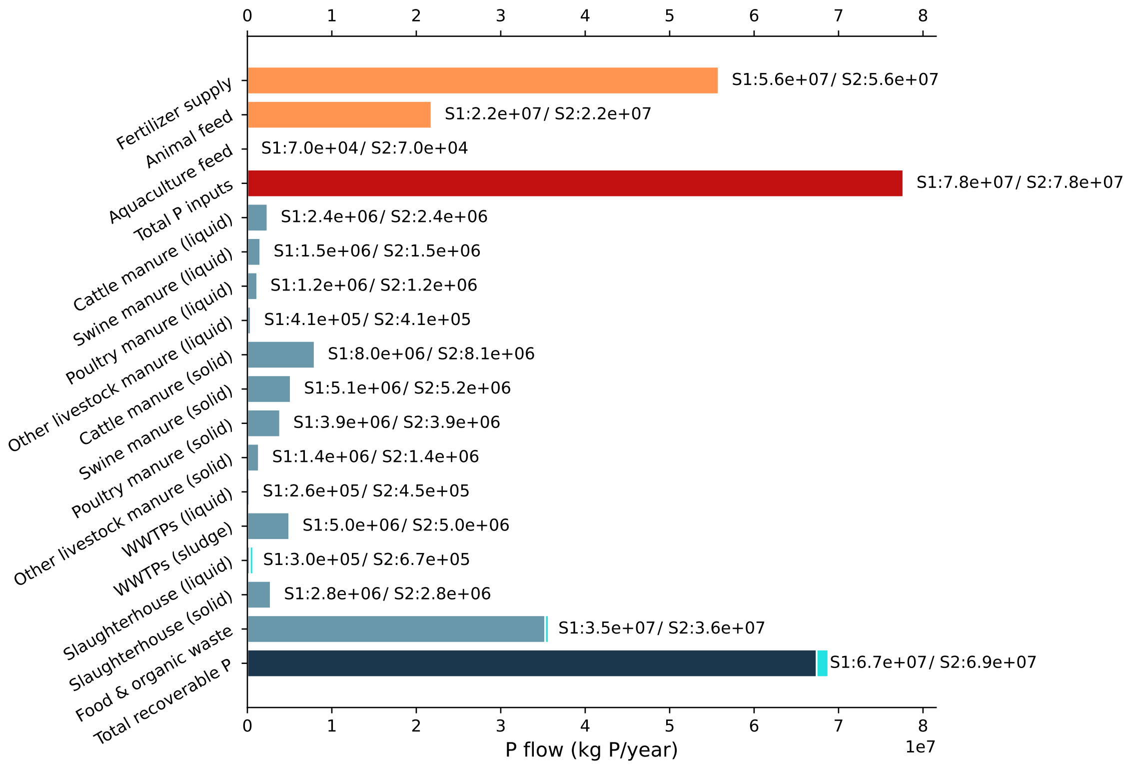

Figure 6: Phosphorus inputs for food production and phosphorus recovered per sector. S1 refers to the scenario minimizing phosphorus recovery cost, while S2 refers to the scenario maximizing phosphorus recovery.

this context, coordinated-market approaches have been proposed to optimize the spatial distribution of phosphorus from regions with surplus of phosphorus to P-deficient locations, minimizing the cost and environmental footprint of the transportation of phosphorus products (Sampat et al., 2019).

4. Conclusions

Phosphorus is a key non-renewable element for many economic sectors, and particularly for the production of food. The current linear economy scheme depletes phosphorus reserves, resulting in supply dependencies from regions holding phosphorus rock reserves, and lead to nutrient pollution, eutrophication, and other environmental concerns related to the end-of-life release of phosphorus into the environment. As a consequence, the recovery and recycling of phosphorus is not only a desirable but a necessary approach for the development of phosphorus sustainable systems. For achieving this goal, the mapping of phosphorus across the different economic sectors is the first stage to identify the main streams for phosphorus recovery. This information allows the estimation of the potential for the recycling of phosphorus in a region.

For the case of Ontario, the best case scenario results in a phosphorus recycling potential of 86% over the phosphorus imported in the province for food production (i.e., excluding the imports of livestock and food produced in other regions). An average phosphorus recovery cost is estimated, although it shows a large variation among different flows. Phosphorus recovery costs are particularly large for phosphorus recovery from manure due to the small scale of the livestock facilities in Ontario. Conversely, phosphorus recovery costs estimated for other regions with larger livestock facilities such as the U.S. Great Lakes area result in significantly lower values, showing the important role of the economies of scale for phosphorus recovery. Nevertheless, considering the region studied as a whole, the average phosphorus recovery cost estimated is around 36 EUR/kg P recovered, which is lower than the economic losses of phosphorus releases into the environment estimated at 74.5 EUR/kg of phosphorus.

The wide difference in costs for the recovery of phosphorus from different flows suggests the need to develop regional cooperative mechanisms to distribute the phosphorus recovery costs. Moreover, further research on the effective distribution of the phosphorus recovered from regions with phosphorus surplus to phosphorus-deficient locations is needed, although there exists some research on the development of coordinated markets for phosphorus recovery and recycling.

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Appendix A. Phosphorus recovery technologies techno-economic data

Table A.1: Phosphorus recovery technologies considered in the study. For the treatment of manure we assumed that the units for the separation of the solid and liquid phases is already implemented in the livestock operations. F denotes the phosphorus recovered as $\mathrm{kg}\ \mathrm{P}_{\mathrm{recovered}}/\mathrm{year}$, 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 1.1. Refs: [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)

Sector	Inflow	Pretreatment	Pretreatment cost (EUR/kg $\mathrm{P}_{\mathrm{recovered}}$)	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	-	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	-	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	-	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	-	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	-	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	-	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	-	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	4-6	[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, 14% of total wastewater P)	-	-	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, 86% of total wastewater 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, 86% of total wastewater 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 separation & food waste	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]

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