

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

Edgar Martín-Hernández^{a,*}, Jorge A. Garcia Hernandez^d, Samantha Gangapersad^c, Tian Zhao^c, Sidney Omelon^c, Roy Brouwer^{d,e}, Céline Vaneeckhaute^{a,b}

^a*BioEngine - Research Team on Green Process Engineering and Biorefineries, Chemical Engineering Department, Université Laval, 1065 Ave. de la Médecine, Québec, QC, G1V 0A6, Canada*

^b*CentrEau, Centre de recherche sur l'eau, Université Laval, 1065 Avenue de la Médecine, Québec, QC, G1V 0A6, Canada*

^c*Department of Mining and Materials Engineering, McGill University, Montréal, Canada*

^d*Department of Economics, University of Waterloo, 200 University Avenue West, Waterloo, ON, N2L 3G1, Canada*

^e*The Water Institute, University of Waterloo, 200 University Avenue West, Waterloo, ON, N2L 3G1, Canada*

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

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

*Corresponding author
Email address: edmah2@ulaval.ca (Edgar Martín-Hernández)

19 in the XIX and XX centuries ([Samreen and Kausar, 2019](#)). The combination of synthetic fertilizers
20 with other modern intensive agricultural techniques have increased the productivity of agriculture
21 and farming industries ([Pingali, 2012](#)). However, the intensive use of fertilizers in agriculture has
22 resulted in the over-application of phosphorus ([Reid and Schneider, 2019](#)), while the run of intensive
23 livestock operations, result in important difficulties in the management of the large amounts of
24 manure produced. This is often spread on lands in the vicinity of the livestock operations, which
25 in turn leads to the accumulation of phosphorus in the soil. Although soil acts as a phosphorus
26 reservoir ([Ehlert et al., 2003](#)), building-up a legacy P that can be used for future crops, it can
27 also be transported to waterbodies by erosion and runoff, resulting in the eutrophication of aquatic
28 ecosystems.

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

41 Although the main uses of phosphorus are in the agri-food sector, phosphorus is also involved
42 in other industrial activities, including steel, chemical, and forestry industries. Henceforth, phos-
43 phorus is a key material for many aspects of human development. As a result, the mapping of
44 phosphorus flows involved in human activities to detect opportunities for recovery and recycling
45 is essential to determine the fraction of phosphorus which recovery is viable, promoting a circular
46 economy that enhances the sustainability of food production systems in terms of resiliency, savings

47 from the reduction of phosphorus imports, and mitigation of phosphorus pollution. on the regions
48 implementing strategies for phosphorus recovery and recycling. The detailed quantification of phos-
49 phorus flows has been addressed in the literature for certain sectors, particularly for the agri-food
50 sector (Boh and Clark, 2020; Zhou et al., 2021; Nesme et al., 2018). In addition, phosphorus flows
51 have also been studied at global (Villalba et al., 2008; Chen and Graedel, 2016) and national scales
52 (Van Dijk et al., 2016; Klinglmair et al., 2015), although these studies tend to aggregate the flows
53 by major sectors, resulting in a lower flow resolution.

54 The works quantifying phosphorus often include qualitative recommendations to improve the
55 phosphorus use efficiency and recycling (Van Dijk et al., 2016; Senthilkumar et al., 2012), but they
56 do not include quantitative assessments on the amount of phosphorus that is feasible to recover along
57 with the costs involved. Conversely, those works focused on estimating the recoverable phosphorus
58 and the associated recovery costs target specific activities such as livestock production (Martín-
59 Hernández et al., 2021; Sampat et al., 2018) and wastewater treatment (Egle et al., 2016; Nättorp
60 et al., 2017). However, a holistic approach mapping the phosphorus flows and identifying the key
61 streams for phosphorus recovery and reuse is a crucial stage to promote the debate about global
62 and regional circular nutrient economies and redistribution systems (Kahiluoto et al., 2021), and to
63 design important aspects of future phosphorus recycling strategies such as the design of coordinated
64 markets (Sampat et al., 2019) and incentive policies (Martín-Hernández et al., 2022).

65 In this work, we intend to perform a holistic approach to phosphorus management, recovery,
66 and recycling through the study of the Canadian province of Ontario. In a first stage, we proceed
67 to map the phosphorus flows involved in the economical sectors of Ontario, i.e., the agricultural,
68 industrial, and urban sectors. These data is used in a second stage to identify the flows in which
69 phosphorus recovery is feasible, estimating the amount of phosphorus that could be recovered within
70 the province. Different phosphorus recovery technologies with technology readiness levels equal or
71 above 6 are evaluated, as well as the phosphorus recovery costs of each one of them. Finally, we
72 discuss the implications that would be derived from implementing active phosphorus recovery and
73 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 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).

100 Phosphorus flows through the imports and exports of animals is estimated using data on ani-
101 mal imports and exports ([Statistics Canada – Statistique Canada, 2021b,c,h](#)) multiplied by their
102 phosphorus to live weight ratios ([Statistics Netherlands, 2012](#)).

103 Phosphorus contained in meat and slaughterhouse waste is based on the number of animals
104 slaughtered reported by both federally and provincially licensed meat plants ([Agriculture and Agri-
105 Food Canada, 2021c,b](#)) multiplied by the concentration of phosphorus in carcasses ([Agriculture
106 and Agri-Food Canada, 2021d](#); [Hayse and Marion, 1973](#); [Brake et al., 1995](#); [Statistics Netherlands,
107 2012](#)).

108 Phosphorus flows associated with the production of milk and eggs is based on provincial produc-
109 tion data ([Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2020a,b](#)),
110 multiplying these products by their average phosphorus concentration ([Health Canada, 2008](#); [Cham-
111 bers et al., 2017](#)).

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

116 The uptake of phosphorus by crops is determined based on the area used in each census division
117 ([Opendatasoft, 2019](#)) to grow each type of crops by census division ([Agriculture and Agri-Food
118 Canada, 2022a,b,c](#)) multiplied by the specific yield and phosphorus content for each crop type
119 ([United States Department of Agriculture, 2009](#)). The phosphorus uptake by crops is divided
120 according to whether it uptake in the grain, fruit or vegetable, or straw and stover components of
121 each type of crop. This is necessary to determine the amount of phosphorus that flows within food
122 or feed (i.e., grains, fruits and vegetables), while straw and stover remain in the field after harvesting
123 as crop residues.

124 A fraction of the phosphorus applied to crop fields as manure of synthetic fertilizer is lost through
125 erosion, runoff, and drainage. The magnitude of this flow depends on a range of factors, including
126 the amount of phosphorus applied; soil composition, texture, and slope; and precipitations, resulting
127 in a complex and data-intensive process for estimating the phosphorus transported out of the crop

128 fields. As an approximation, we have estimated the phosphorus losses by using export coefficients
129 determined for crop fields in Ontario corrected to account for both surface and subsurface runoffs
130 for synthetic fertilizers (1.267 kg/ha/year), and liquid and solid manure (2.548 kg/ha/year and
131 1.717 kg/ha/year respectively) (Zhang et al., 2015; Wang et al., 2018; Tan and Zhang, 2011). In
132 addition, a fraction of the P supplied to crop fields is not taken up by the plants and remains in
133 soil, resulting in the accumulation of P over time as a result of synthetic fertilizer and manure over
134 over sustained periods of time, often applying phosphorus in greater quantities than crops require
135 to ensure satisfactory yields (Reid et al., 2019). This buildup is often referred to as “legacy P”,
136 and it is estimated as the balance between phosphorus inflows to crop fields (application of manure
137 and synthetic fertilizers) and outflows (crop food and feed products, crop residues, and phosphorus
138 losses by erosion and runoff).

139 Regarding greenhouse crops, the data available was limited, resulting in an estimation of phos-
140 phorus applied as synthetic fertilizers based on the sum of phosphorus uptake by greenhouse crops
141 and phosphorus releases from greenhouse irrigation systems also known as greenhouse nutrient feed-
142 water (GNF) systems (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs,
143 2021). The phosphorus uptake by greenhouse crops is determined by multiplying the production
144 of greenhouse crops (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs,
145 2022) by the phosphorus content of each vegetable type (United States Department of Agriculture,
146 2009). The phosphorus releases from the GNF systems was estimated based on the average con-
147 centration of phosphorus in GNF outlet streams for Ontario, 33.6 mg/L (Ontario Ministry of the
148 Environment, Conservation and Parks, 2012), and the total water discharges from GNF systems,
149 assuming that the water discharges are equivalent to 25% of the total water applied in greenhouses,
150 which corresponds with the worst-case scenario of no water recirculation in the GNF systems (On-
151 tario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2021). The average water
152 consumption in greenhouses in Ontario was assumed to be 1,000 L/m²/year (Ontario Ministry
153 of Agriculture and Food and the Ministry of Rural Affairs, 2011). We have also estimated the
154 phosphorus releases from the seasonal workers live in households in the vicinity of the greenhouses
155 that may use septic systems, considering that the seasonal labour force in Ontario greenhouses is

156 estimated to be 6,699 workers ([Government of Canada, 2022](#)), and an average phosphorus load rate
157 of f 0.0156 kg P/person/week from septic systems ([Oldfield et al., 2020](#)).

158 Phosphorus enters aquaculture systems as fish feed, primarily in the growth of trouts. A frac-
159 tion of this phosphorus goes to the fish and the remainder is discharged into aquatic ecosystems as
160 aquaculture effluents ([Ontario Ministry of the Environment, Conservation and Parks, 2019](#)). The
161 total phosphorus in fish produced in Ontario is calculated multiplying the fish production ([Statis-
162 tics Canada - Statistique Canada, 2021](#)) by their phosphorus content ([Health Canada, 202](#)), while
163 the phosphorus content in the aquaculture waste effluents of Ontario is estimated to be 10 kg of
164 phosphorus per ton of fish produced ([Bureau et al., 2003](#)). The phosphorus in Ontario fish feed
165 that is supplied to aquaculture, is estimated to be the sum of the phosphorus in the fish produced
166 and the phosphorus in aquaculture effluent.

167 *2.2.2. Industrial sector*

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

170 Processed food imports and exports are estimated scaling each type of food traded in Canada
171 ([Statistics Canada - Statistique Canada, 2022e](#)) with the population of Ontario ([Statistics Canada -
172 Statistique Canada, 2022c](#)). The phosphorus contained in each type of imported and exported food
173 is estimated multiplying the amount of each type of traded food by its phosphorus content ([Health
174 Canada, 202](#)). Phosphorus flows in the form of food and organic waste are based on applying food
175 loss factors for the steps associated with food processing, from the production of food raw materials
176 to consumption ([FAO, 2011](#)), considering the food production and import values estimated in
177 Section 2.2.1.

178 The steel industry is the first non-food sector in terms of phosphorus use. The main phosphorus
179 inflows of steel manufacturing are associated with the use of iron ore, coal, and coke, while the main
180 outflow of phosphorus is within slag, a by-product of steelmaking. During steelmaking, most of the
181 impurities, including phosphorus separate into the slag phase. It must be noted that, although some
182 minor amounts of phosphorus can be desired in steel for making anti-corrosion surface coatings,

183 it is largely considered an impurity in the steel manufacturing process. Phosphorus in these flows
184 is estimated multiplying their average phosphorus content (0.06% P in iron ore, 0.05% P for coal,
185 0.4% P in slag, and 0.01% in steel) ([Yokoyama et al., 2007](#)) by the steel production capacity of
186 the facilities located in Ontario ([Cheminfo Services Inc., 2019](#); [Algoma Steel Inc., 2022](#); [Stelco Inc.,](#)
187 [2022](#); [Pollution Probe, 2022](#)) and the imports and exports of these materials ([World Integrated](#)
188 [Trade Solution, 2022](#); [Statistics Canada - Statistique Canada, 2022a](#)). The P in slag is estimated
189 using component balancing.

190 Phosphorus flows in Ontario's forestry industry includes wood harvesting, wood products man-
191 ufacturing, as well as the production of pulp and paper. The estimation of these phosphorus flows
192 are the result of multiplying the production data of wood, wood products, pulp and paper, and their
193 respective imports, exports, and waste streams ([Canadian Forest Service, 2020](#); [Statistics Canada](#)
194 [- Statistique Canada, 2022a](#)), by their average phosphorus content. The average phosphorus content
195 used for wood is 0.01% ([Sardans and Peñuelas, 2013](#)) and 0.005% is estimated for pulp and paper
196 products, using component balancing.

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

203 *2.2.3. Urban sector*

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

207 Phosphorus flows through WWTPs is estimated combining data from the National Pollutant
208 Release Inventory (NPRI) ([Environment and Climate Change Canada, 2021a](#)), a public database
209 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 validated using the Municipal Treated Wastewater Effluent
 (MTWE) database ([Ontario Ministry of the Environment, Conservation and Parks, 2021](#)), 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 flows through sludge disposals. This methodology is shown in Figure
 1.

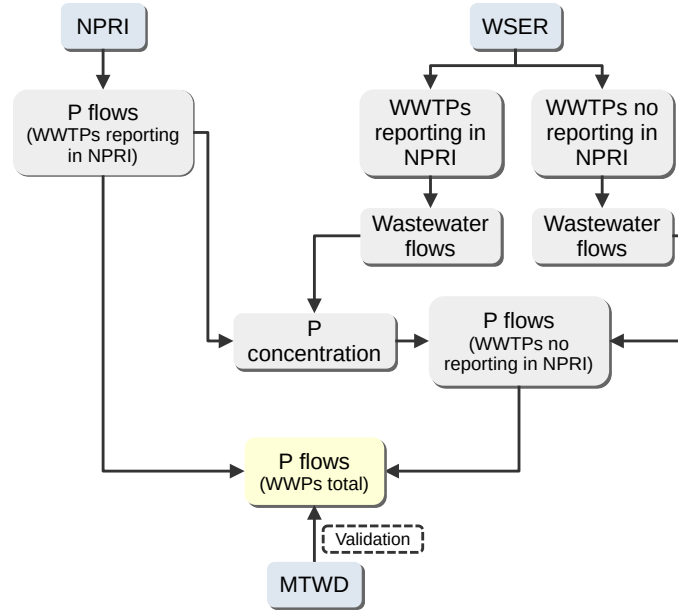


Figure 1: Procedure for estimating phosphorus flows through wastewater treatment plants.

There exist households that are not connected to any sewer systems, 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 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 - Statistique Canada, 2015), which are inhabited by an average of 2.58 individuals (Statistics Canada - Statistique 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 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 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.

251 Phosphorus in manure represent an important flow within the agricultural sector. The tech-
252 niques used for phosphorus recovery from cattle and swine manure differ for the liquid and solid
253 fractions. Struvite precipitation is the dominant technology for phosphorus recovery from liquid
254 manure, existing different processes for struvite production based on the type of reactors used with
255 similar recovery efficiencies but different treatment capacities, and thus different recovery costs
256 (Martín-Hernández et al., 2021). Additionally, there exist modular processes based on physical
257 separations oriented to small-scale intensive livestock facilities (Church et al., 2018). The recovery
258 of phosphorus from the solid fraction of manure involves the incineration of the waste, and the
259 further processing of the ashes, recovering phosphorus precipitates or phosphoric acid (Jupp et al.,
260 2021; Egle et al., 2016). Phosphorus recovery from poultry litter is based on acid extraction and
261 further precipitation (Szögi et al., 2008).

262 Slaughterhouse waste is a flow from the food processing industry which can be targeted for
263 phosphorus recovery. It should be noted that slaughterhouse is comprised by a liquid (slaughter-
264 house wastewater) and a solid fraction (animal carcass waste). Similarly to phosphorus recovery
265 from liquid manure, phosphorus recovery from slaughterhouse wastewater is performed through
266 through struvite precipitation (AMPC, 2018), while the animal carcass waste is incinerated
267 and phosphorus is recovered from ashes in form of calcium carbonate or phosphoric acid (Jupp
268 et al., 2021).

269 Municipal wastewater contains significant amounts of phosphorus that can be recovered. It
270 must be noted that phosphorus outflows from WWTPs are divided into phosphorus contained
271 in the treated water and phosphorus contained in sludge. Phosphorus contained in water can
272 be recovered through the formation of precipitates such as struvite or calcium phosphate, while
273 phosphorus contained in sludge can be recovered either through the direct processing of sludge
274 producing precipitates, or from sludge ashes after an incineration stage, obtaining different products
275 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 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 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 of 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.

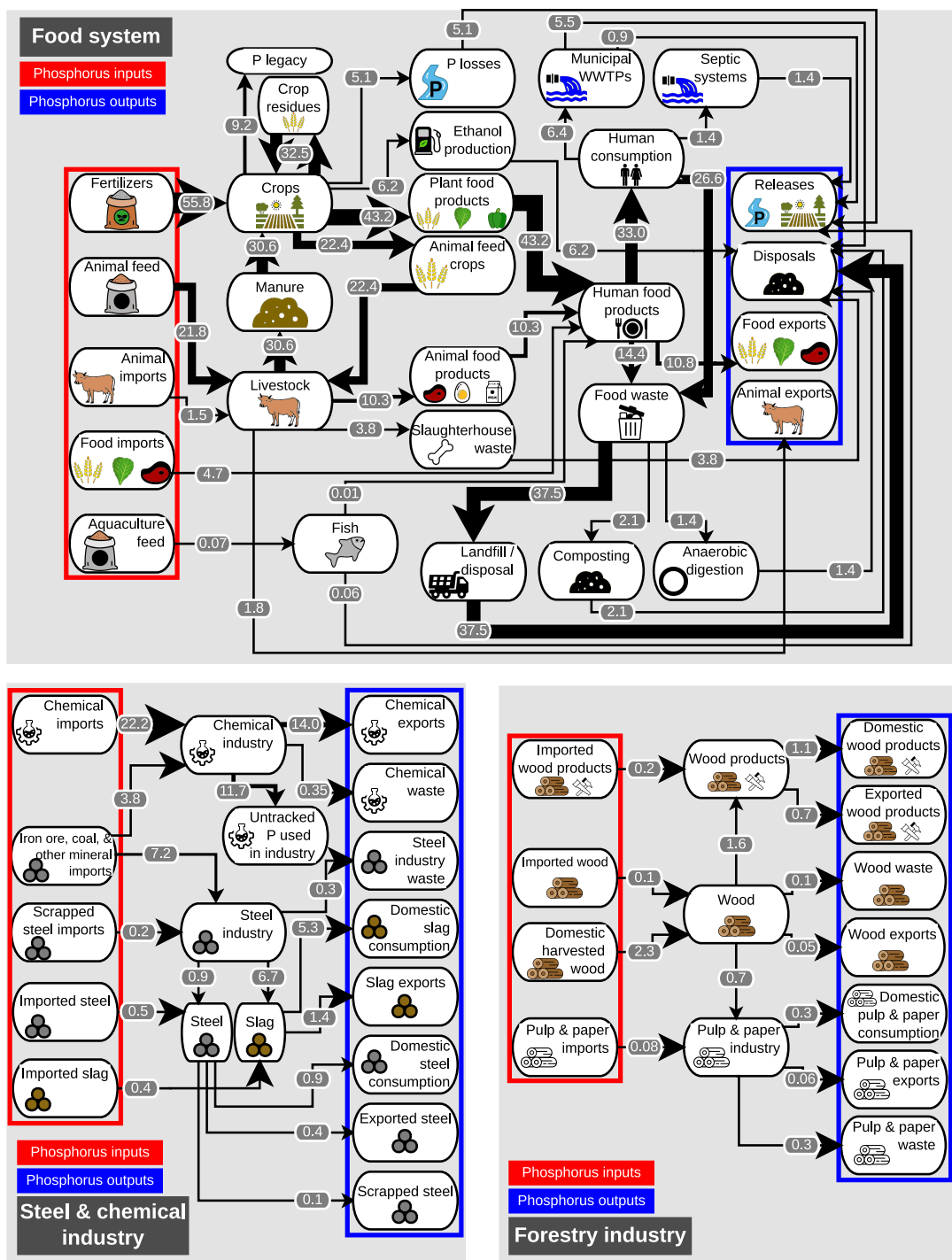


Figure 2: Phosphorus flows in the province of Ontario (kt/year). The streams within red rectangles denote phosphorus inflows into the province, while those streams within blue rectangles denote phosphorus outflows out of the province.

299 Chemical industry involve significant phosphorus flows, importing 22.2 kt/year into the province,
300 while the exports represent 14.0 kt/year. This sector produces 0.35 kt/year of phosphorus that is
301 classified as waste. However, an important fraction of phosphorus used by this sector (11.7 kt/ton)
302 cannot be tracked and, therefore, it is unknown what is the real amount of phosphorus disposed
303 as waste. Steel production imports 8.3 kt/year of phosphorus, of which 7.0 kt/year ends as steel
304 waste or slag, while the phosphorus outflows through steel materials are 1.4 kt/year.

305 Phosphorus imports from the forestry industry are 0.38 kt/year, while 2.3 kton/year of phos-
306 phorus is taken from local wood harvested within Ontario. This sector releases 0.4 kton/year of
307 phosphorus in the form of wood and pulp waste, while 0.81 kt/year of phosphorus is exported out
308 of the province as wood, manufactured wood products, pulp, and paper.

309 *3.2. Potential of phosphorus recovery in Ontario*

310 The potential for phosphorus recovery in the province of Ontario is assessed in this section.
311 As shown in Section 2.3, different processes can be employed for the recovery of phosphorus from
312 the same stream. However, each system is designed for operating under certain conditions and
313 they have different processing capacities. As a result, phosphorus recovery efficiency and cost may
314 vary between technologies for the treatment of the same flow. In order to explore this variability
315 between phosphorus recovery systems, all the systems described in Table A.1 are evaluated. The
316 results obtained in terms of phosphorus recovered and recovery cost for each technology and flow
317 are collected in the Supplementary Material. Two scenarios are selected for deeper analysis, the
318 minimum cost scenario, in which the most economical technology is selected, and the maximum
319 recovery scenario, in which the phosphorus recovery system selected is the one recovery the largest
320 amount of phosphorus.

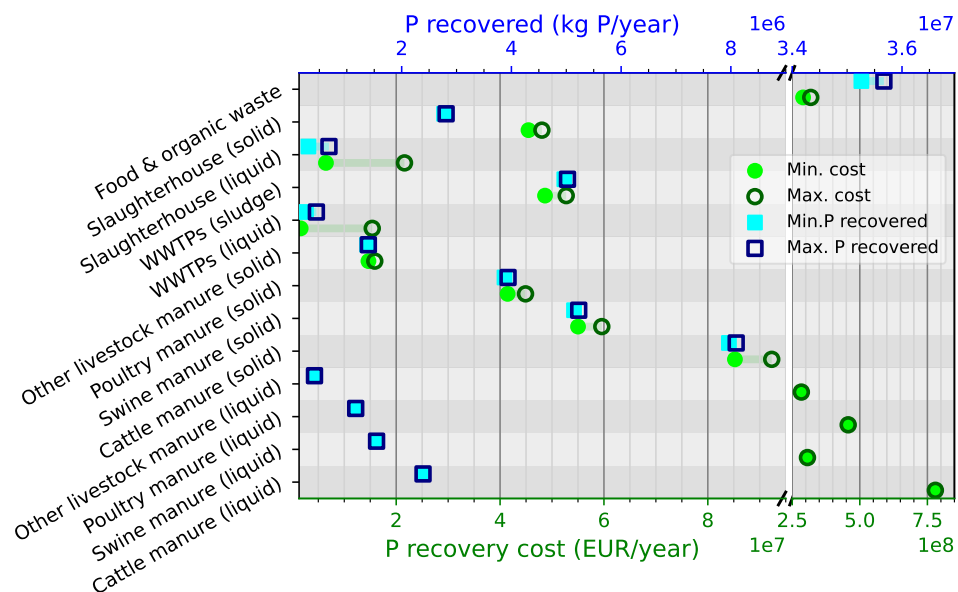


Figure 3: Phosphorus recovered and phosphorus recovery cost in the province of Ontario by flow. Note that the scale of bottom x-axes is different.

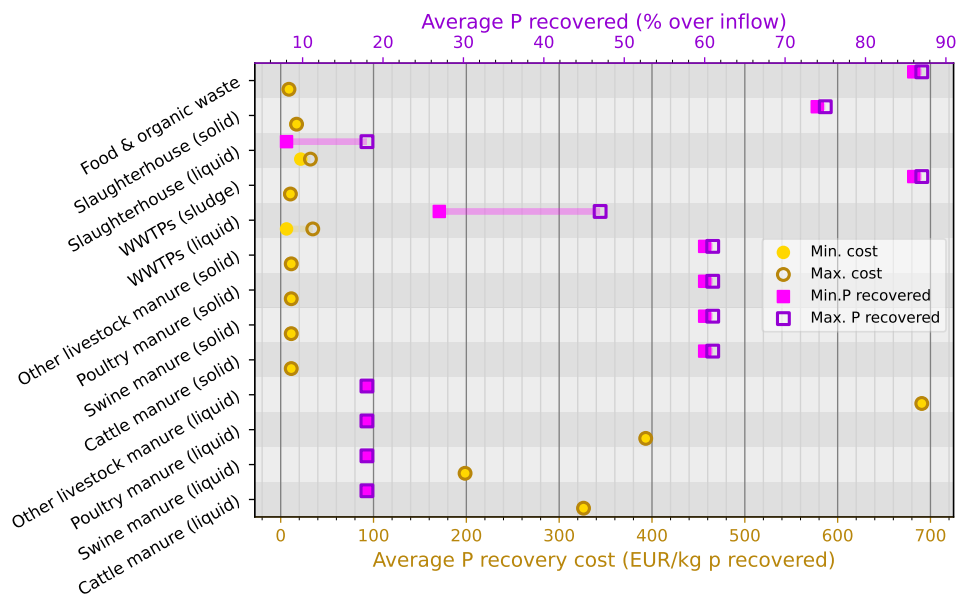


Figure 4: Average phosphorus recovered and average phosphorus recovery cost per kilogram of phosphorus recovered in the province of Ontario by flow.

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 - Statistique 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 - Statistique 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 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 largest 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

349 general terms the small size of the livestock operations in Ontario results in high phosphorus
 350 recovery costs, whose values range between 200 and 700 EUR/kg P recovered. These costs are
 351 significantly higher than the phosphorus recovery costs reported by [Martín-Hernández et al. \(2022\)](#)
 352 for the comparatively larger livestock operations of the U.S. states in the Great Lakes area, whose
 353 average sizes range from 630 and 2,600 animal units, resulting in phosphorus recovery costs between
 354 13 and 73 USD/kilogram of phosphorus recovered. The phosphorus recovery efficiency is similar for
 355 all livestock types since the processes selected are the modular physical separation system MAPHEX
 356 due to the small scale of the livestock facilities. It was not possible to evaluate the effect of the
 357 economies of scale for the processes intended to phosphorus recovery from the solid fraction of
 358 manure due to the lack of techno-economic data available for them.

359 *3.2.2. Industrial and urban sector*

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

363 Slaughterhouse waste is an industrial flow from which phosphorus can be effectively recovered
 364 ([AMPC, 2018](#)). Data on individual capacities for the slaughterhouses in Ontario is not available
 365 to estimate the effect of the economies of scale on the cost of phosphorus recovery. Therefore,
 366 average slaughterhouse capacities are considered, which values are 104,017, 802,186, and $14.4 \cdot$
 367 10^6 cattle, hog, and poultry heads slaughtered/(facility \cdot year) respectively ([Agriculture and Agri-](#)
 368 [Food Canada, 2021a; INAC Services, 2014](#)). Considering the inventory of slaughtered animals
 369 reported by [Agriculture and Agri-Food Canada \(2021c,b\)](#), 7, 6, and 17 cattle, hog, and poultry
 370 slaughtering facilities are obtained, with associated phosphorus flows of 317.4, 103.5, and 53.2
 371 metric tonnes/(facility \cdot year) respectively. Phosphorus flows from slaughtered sheep and rabbit are
 372 considered negligible due to the low number of animals slaughtered. Figure 3 shows that most of
 373 phosphorus can be recovered from the solid fraction of waste due to its larger phosphorus content.
 374 The variations between the minimum cost and maximum recovery scenarios are not significant for
 375 the solid slaughterhouse waste flow. However, for slaughterhouse wastewater phosphorus recovery

for the maximum recovery scenario increase 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 second 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% - 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 exist 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 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 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 Bureau, 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.

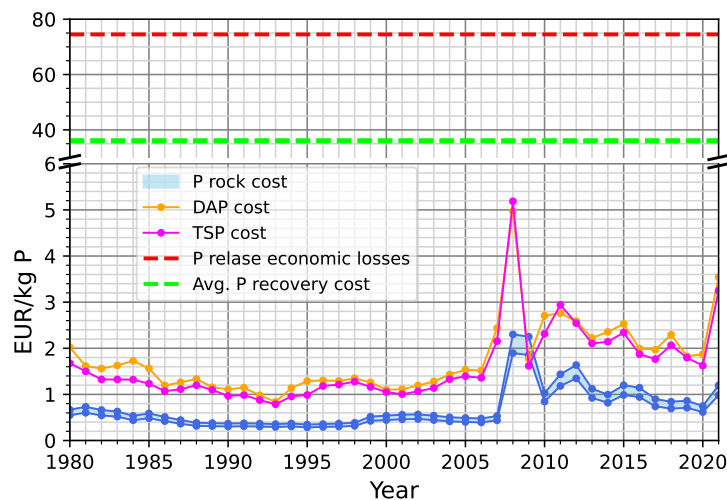


Figure 5: Average phosphorus recovery cost in Ontario, economical losses derived from the releases of phosphorus into the environment (Sampat et al., 2021), and temporal evolution of prices for different phosphorus commodities. Note that the scale of y-axis is different for top and bottom axes.

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 produce elsewhere, could be recovered and recycled in the best case scenarios where no phosphorus losses occur between the recovery and the reuse stages. An effective recycling of phosphorus implies the redistribution of this material from the locations where it is released to the livestock operations where it is used for livestock raise, or to phosphorus-deficient cropfields, which in turn involves the transportation of phosphorus products as the last stage before the use final use of the recovered phosphorus. It must be considered that the transportation of phosphorus

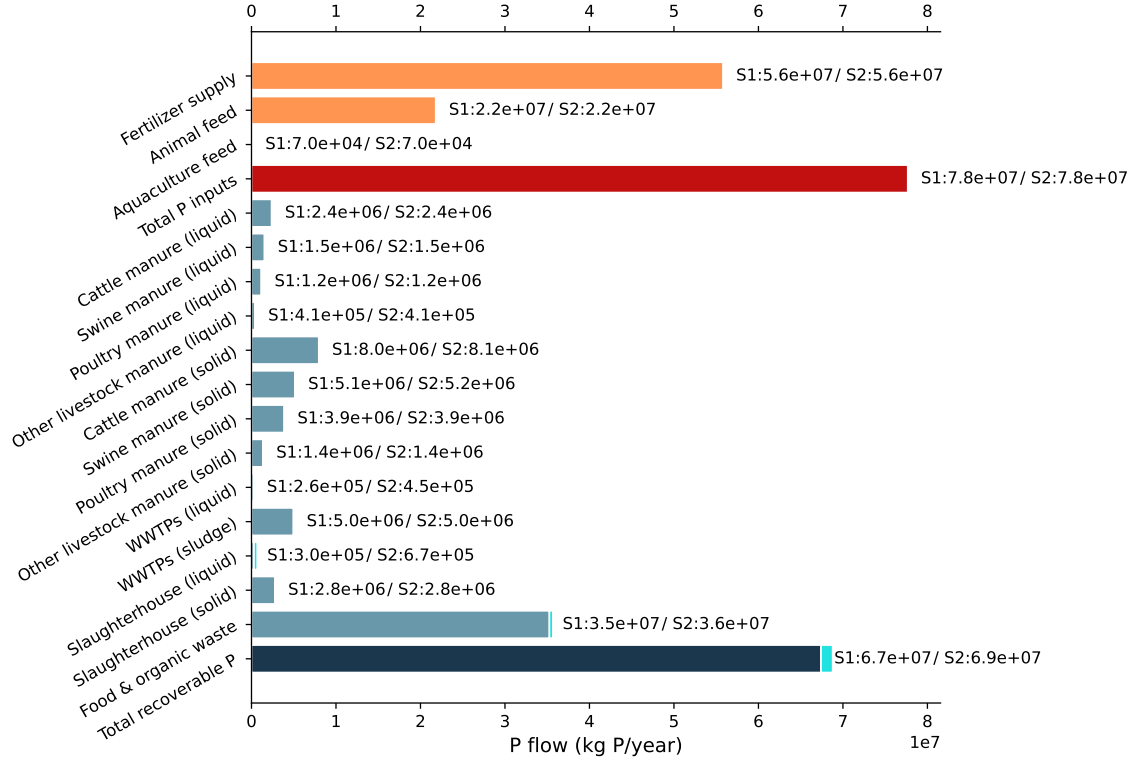


Figure 6: Phosphorus inputs for food production and phosphorus recovered per sector. S1 refers to the scenario minimizing phosphorus recovery cost, while S2 refers to the scenario maximizing phosphorus recovery.

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 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 deplete phosphorus reserves, resulting in supply dependencies from regions holding phosphorus rock reserves, and it is the sources of nutrient pollution, eutrophication, and other environmental concerns relates with 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 result in a phosphorus recycling potential up to 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 is 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 of costs for the recovery of phosphorus from different flows suggest the need develop regional cooperative mechanisms to distribute the phosphorus recovery costs. Moreover, further research in the effective distribution of the phosphorus recovered from regions with phosphorus surplus to phosphorus-deficient locations is needed, although there exist some research on the development of coordinated markets for phosphorus recovery and recycling.

5. Acknowledgments

Please add your acknowledgements

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 kg $P_{\text{recovered}}/\text{year}$, while $[x]$ 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 $P_{\text{recovered}}$)	Technology	Type	P recovery potential (% related to inflow)	P recovery cost (EUR/kg $P_{\text{recovered}}$)	TRL	Ref tech
Agriculture	Cattle and swine manure, liquid phase (30% of total manure P)	Solid-liquid separation	-	Multiform	Struvite	60	$25.7 + 1.10 \cdot 10^{-4} \cdot [1.19 \cdot 10^{-4} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Crystallactor	calcium phosphate	60	$3.53 + (2.30 \cdot 10^6 + 0.71 \cdot [3.32 \cdot 10^{-5} \cdot F]) \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Ostara Pearl 500	Struvite	60	$12.57 + 2.30 \cdot 10^6 \cdot [7.02 \cdot 10^{-5} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Ostara Pearl 2K	Struvite	60	$12.57 + 3.10 \cdot 10^6 \cdot [1.83 \cdot 10^{-5} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Ostara Pearl 10K	Struvite	60	$12.57 + 10.00 \cdot 10^6 \cdot [3.65 \cdot 10^{-6} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Nurelys	Struvite	60	$10.37 + 1.38 \cdot 10^6 \cdot [2.24 \cdot 10^{-5} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[1]
	Cattle and swine manure, solid phase (70% of total manure P)	Solid-liquid separation	-	MAPHEX	Solid	90	$184.67 + 0.30 \cdot 10^6 \cdot [2.47 \cdot 10^{-4} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	6	[1]
		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	6	[2,3,4]
	Poultry litter	Incineration	8.9	RecoPhos	Mineral	87	2.5	9	[2,3,4]
		Incineration	8.9	Thermophos	P4	81	2.7	9	[2,3,4]
		-	-	Quick wash	Solid precipitate	70	4.4	4-6	[5]
		-	-	Multiform	Struvite	84	$22.6 + 1.10 \cdot 10^6 \cdot [1.05 \cdot 10^{-4} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[6]
Urban & industrial	Slaughterhouse waste, liquid phase (14% of total slaughterhouse P)	Incineration	-	Ostara Pearl 500	Struvite	58	$15.60 + 2.30 \cdot 10^6 \cdot [8.70 \cdot 10^{-5} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		Incineration	-	Ostara Pearl 2K	Struvite	58	$15.60 + 3.10 \cdot 10^6 \cdot [2.26 \cdot 10^{-5} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		Incineration	-	Ostara Pearl 10K	Struvite	58	$15.60 + 10.00 \cdot 10^6 \cdot [4.53 \cdot 10^{-6} \cdot F] \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		Incineration	14.6	EcoPhos	Phosphoric acid	82	4.5	6	[2,3,7]
	Slaughterhouse waste, solid phase (86% of total slaughterhouse P)	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]
	WWTPs (liquid phase, 14% of total wastewater P)	Incineration	14.6	RecoPhos	Mineral	87	2.5	9	[2,3,7]
		Incineration	14.6	Thermophos	P4	81	2.7	9	[2,3,7]
		-	-	Crystallactor	Struvite/ Calcium phosphate	38	$305,920 \cdot \left(\frac{F}{21,966}\right)^{0.89} \cdot \frac{1}{F}$	9	[3]
		-	-	Ostara Pearl	Struvite	20	$130,856 \cdot \left(\frac{F}{13,136}\right)^{0.36} \cdot \frac{1}{F}$	9	[3]
Urban & industrial	WWTPs (sewage sludge, 86% of total wastewater P)	-	-	P-RoC	Calcium phosphate	27	$75,970 \cdot \left(\frac{F}{17,357}\right)^{0.78} \cdot \frac{1}{F}$	6	[3]
		-	-	REM-NUT	Struvite	47	$977,933 \cdot \left(\frac{F}{36,876}\right)^{0.94} \cdot \frac{1}{F}$	6	[3]
		-	-	AirPrex	Struvite	15	$74,195 \cdot \left(\frac{F}{9,555}\right)^{0.38} \cdot \frac{1}{F}$	9	[3]
		-	-	PRISA	Struvite	18	$186,923 \cdot \left(\frac{F}{17,836}\right)^{0.43} \cdot \frac{1}{F}$	6	[3]
	WWTPs (sewage sludge, 86% of total wastewater P)	-	-	Stuttgart process	Struvite	40	$581,730 \cdot \left(\frac{F}{37,286}\right)^{0.89} \cdot \frac{1}{F}$	9	[3]
		-	-	Giffoni process	Struvite	40	$400,384 \cdot \left(\frac{F}{37,286}\right)^{0.82} \cdot \frac{1}{F}$	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]
	WWTPs (sewage sludge ash SSA, 86% of total wastewater P)	-	-	MEPHREC	P rich slag	68	$1,154,473 \cdot \left(\frac{F}{44,676}\right)^{0.61} \cdot \frac{1}{F}$	6	[3]
		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]
	Organic municipal sewage sludge & food waste	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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