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

Université Laval team[a,*], McGill University team[b], University of Waterloo team[c]

[a] *Université Laval*
[b] *McGill University*
[c] *University of Waterloo*

Abstract

Phosphorus is a key non-renewable element for food production and other economic activities. Phosphorus is used intensively in the food production and consumption system, however, its sustained emissions over time lead to nutrient pollution and eutrophication of ecosystems. In this work, we map the phosphorus flows through Ontario's economic sectors, and we identify the phosphorus recovery opportunities and recycling potential. These mainly target flows associated with food production and processing, including wastewater and food waste. Up to 86% of phosphorus imports for food production could be covered by recycled phosphorus, with an average recovery cost of 36 EUR/kg. This is lower than the estimated economic losses derived from the release of phosphorus into the environment, but significantly higher than fossil-based phosphorus products. Additionally, there exist a wide variation on phosphorus recovery costs from different streams, which suggest the need of exploring cooperative approaches for effective phosphorus recovery at regional scale.

1. Introduction

Phosphorus is an essential for production of food which has been intensively used for crop and livestock production since the development of synthetic fertilizers in the XIX and XX centuries (Samreen and Kausar, 2019). The combination of synthetic fertilizers with other modern intensive agricultural techniques have increased the productivity of agriculture and farming industries (Pingali, 2012). However, the intensive use of fertilizers in agriculture has resulted in the over-application of phosphorus (Reid and Schneider, 2019), while the run of intensive livestock production facilities,

*Corresponding author
Email address: edgar.martin-hernandez.1@ulaval.ca (Université Laval team)

also known as concentrated animal feeding operations (CAFOs) (U.S. Department of Agriculture, 2011), result in important difficulties in the management of the large amounts of manure produced, which is often spread in lands in the vicinity of CAFOs, which also leads to the accumulation of phosphorus in soil. Soil acts as a phosphorus reservoir (Ehlert et al., 2003), building-up a legacy P that can be used for future crops, but also can be transported to waterbodies by erosion and runoff leading to the eutrophication of aquatic ecosystems.

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

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

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

2. Methods

2.1. Spatial 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 refers the reader to the methodology described in Pollution Probe (2022).

2.2.1. Agricultural sector

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

Phosphorus in livestock feeding and manure is estimated based on the number and type of animals reported for Ontario in the Census of Agriculture (Statistics Canada – Statistique Canada, 2021a,e,c,d,b), 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. 305 (Yang et al., 2007).

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

Phosphorus in fertilizer applied to open fields in Ontario is estimated based on the amount of fertilizer products traded to Ontario's agricultural markets containing 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 uptake in the grain, fruit or vegetable, or straw and stover components of each type of crop. This is necessary to determine the amount of phosphorus that flows within food or feed (i.e.,grains, fruits and vegetables) while straw and stover remain in the field after harvesting as crop residues.

A fraction of the phosphorus applied to crop fields as manure of synthetic fertilizer is lost through erosion, runoff, and drainage. This transportation of phosphorus depends on a range of factor, including the amount of phosphorus applied; soil composition, texture, and slope; and precipitation, resulting in a complex and data-intensive process for estimating the phosphorus transported out of the crop fields. As an approximation, we have estimated the phosphorus losses by using export coefficients determined for crop fields in Ontario 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).

A fraction of the P supplied to crop fields is not taken up by the plants and remains in soil, resulting in the accumulation of P over time as a result of synthetic fertilizer and manure over over sustained periods of time, often applying phosphorus in greater quantities than crops require to ensure satisfactory yields (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).

Regarding greenhouse crops, the data available was limited, resulting in an estimation of phosphorus applied as synthetic fertilizers based on the sum of phosphorus uptake by greenhouse crops (i.e., tomatoes, peppers, and cucumbers)119 and the phosphorus releases from greenhouse irrigation systems (greenhouse nutrient feedwater systems (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2021) systems. 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 was estimated based on the average concentration of phosphorus in GNF outlet streams of Ontario (33.6 mg/L) (Ontario Ministry of the Environment, Conservation and Parks, 2012) and the total water discharges from GNF systems, assuming that water discharges from GNF systems is equivalent to 25% of the total water applied in greenhouses, which corresponding with the worst-case scenario of no water recirculation in the GNF system (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 live in households in the vicinity of the greenhouses that may use septic systems, considering that the seasonal labour force in Ontario greenhouses is estimated to be 6,699 workers (Government of Canada, 2022), and an average phosphorus load rate of f 0.0156 kg P/person/week from septic systems (Oldfield et al., 2020).

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

2.2.2. Industrial sector

Phosphorus flows through imports, production, exports and waste for the steel, forestry, and food and beverage, industries of Ontario were mapped. The steel industry is the first non-food sector in terms of phosphorus use. The main phosphorus inflows of steel manufacturing are associated with the use of iron ore, coal, and coke, while the main outflow of phosphorus is within slag, which remove most of the impurities from steel, including phosphorus. It must be noted that, although some minor amounts of phophosphorus can be desired in steel for making anti-corrosion surface coatings, it is largely considered an impurity in the steel manufacturing process. Phosphorus in these flows is estimated multiplyting their average phosphorus content (0.06% P in iron ore, 0.05% P for coal, 0.4% P in slag, and 0.01% in steel) (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).

Phosphorus flows in Ontario's forestry industry includes wood harvesting, wood products manufacturing, as well as the production of pulp and paper. The estimation of these phosphorus flows are the result of multiplying the production data of wood, wood products, pulp and paper, and their retrospectives imports, exports, and waste streams (Canadian Forest Service, 2020; Statistics Canada - Statisque Canada, 2022a), by the average phosphorus content, which is assumed to be 0.01% for wood (Sardans and Peñuelas, 2013) and 0.005% for pulp and paper products.

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

Regarding other industrial activities which could involve the use of phosphorus, the local production of phosphorus is assumed to be negligible since phosphorus is not mined or refined in Ontario, and the synthetic phosphorus fertilizer imports are accounted in the agricultural section. The general chemical facilities located in Ontario report 350 t/year of phosphorus as waste **??**, in addition of imports and exports of chemical products. However, there exist a significant fraction of phosphorus used in the industrial sector that 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 is 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, including industrial facilities, 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 the federal, provincial, and municipal level. The estimations on phosphorus flows through WWTPs are valitaed 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 disposals and transfers. This methodology is shown in Figure 1

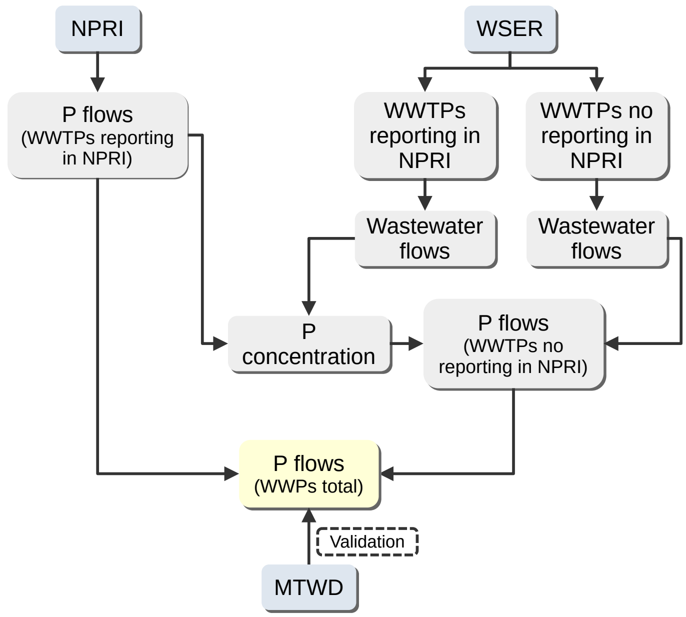

Figure 1: Procedure for estimating phosphorus flows through wastewater treatment plants.

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

Phosphorus flows in the form of food and organic waste are based on applying food loss factors for the steps associated with food processing (FAO, 2011), considering the food production and import values estimated in Section 2.2.1.

2.3. Phosphorus recovery techniques

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

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

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

Phosphorus in manure represent an important flow within the agricultural sector. The techniques used for phosphorus recovery from cattle and swine manure differ for the liquid and solid fractions. Struvite precipitation is he dominant technology for phosphorus recovery from liquid manure, existing different processes for struvite production based on the type of reactors used with similar recovery efficiencies but different treatment capacities, and thus different recovery costs (Martín-Hernández et al., 2021). Additionally, there exist modular processes based on physical

Table 1: Phosphorus recovery techniques considered in the study. F denotes the phosphorus recovered as $\mathrm{kg\ P_{recovered}/year}$, while $\lceil x \rceil$ represent the ceiling function applied to x. The definition of annual capital charge ratio ($ACCR$) can be found in the Supplementary Material, Section ??.

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

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

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

Municipal wastewater contains significant amounts of phosphorus that can be recovered. It must be noted that phosphorus outflows from WWTPs are divided into 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, while phosphorus contained in sludge can be recovered either through the direct processing of sludge producing precipitates, of 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 the production and processing of food (including the treatment of wastewater), the flow of phosphorus used in the steel and chemical industries, and the phosphorus involved in the forestry industry.

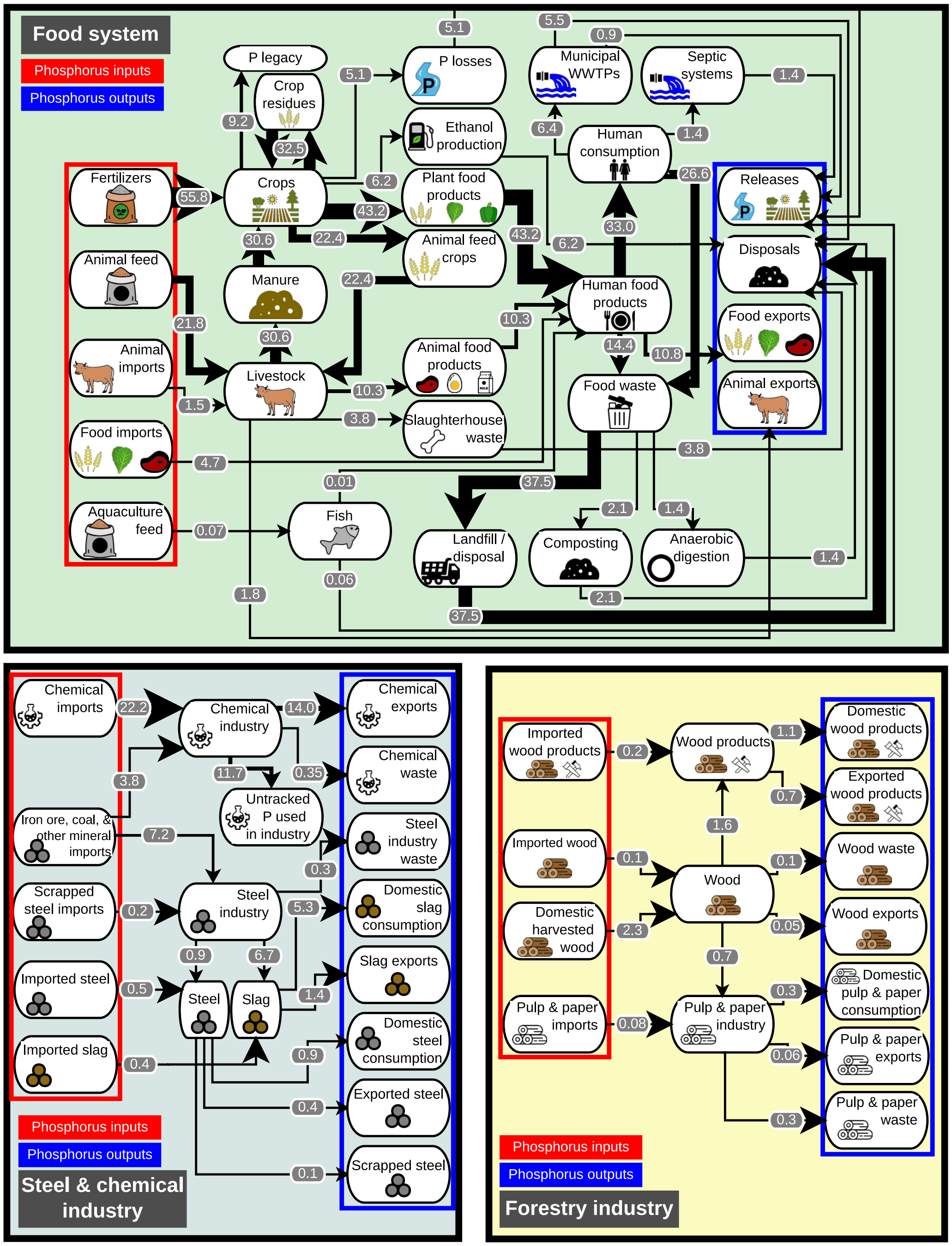

Figure 2: Phosphorus flows in the province of Ontario (kt/year). The streams within red rectangles denote phosphorus inflows into the province, while those streams within blue rectangles denote phosphorus outflows out of the province.

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

Chemical industry involve significant 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 fraction of this phosphorus can result as waste. Steel production imports 8.3 kt/year of phosphorus, of which 7.0 kt/year ends as steel wast or slag, while the phosphorus flows in steel materials are 1.4 kt/year.

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

3.2. Potential of phosphorus recovery in Ontario

The potential for phosphorus recovery in the province of Ontario through the deployment of different processes for the recovery of phosphorus from different flows is assess in this section. As shown in Section 2.3, different processes can be employed for the recovery of phosphorus from the same stream. However, each system is design for operating under certain conditions and they have different processing capacities. As a result, phosphorus recovery efficiency and cost will differ between technologies for the treatment of the same flow. In order to explore this variability between phosphorus recovery systems, all the systems described in Table 1 are evaluated. The results obtained in terms of phosphorus recovered and recovery cost for each technology and flow are collected in the Supplementary Material. Two scenarios are selected for deeper analysis, the minimum cost scenario that selects the most economical technology, and the maximum recovery scenario, comprised by the phosphorus recovery system which deployment result in the largest phosphorus recovery.

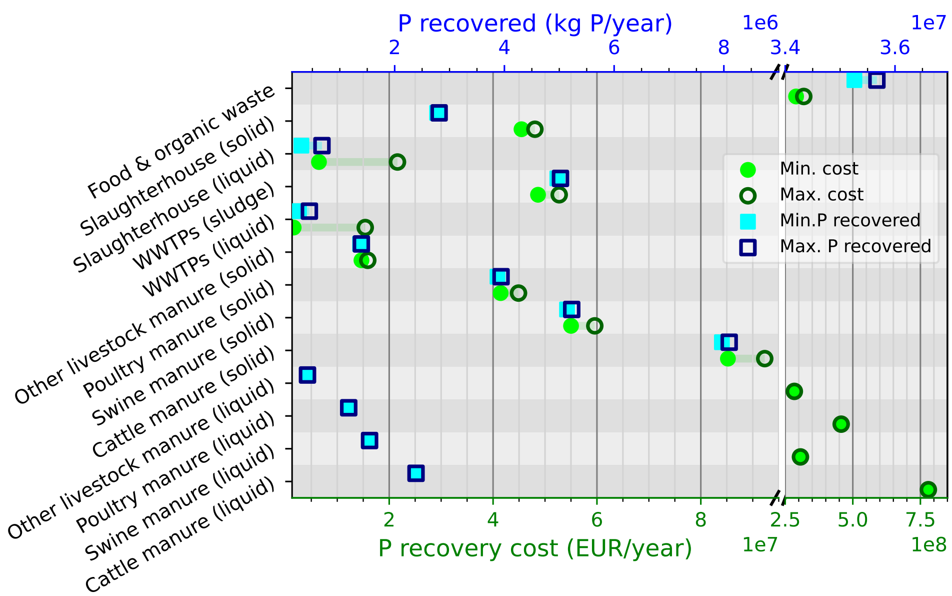

Figure 3: Phosphorus recovered and phosphorus recovery cost in the province of Ontario by flow. Note that the scale of bottom x-axis is different for left and right axes.

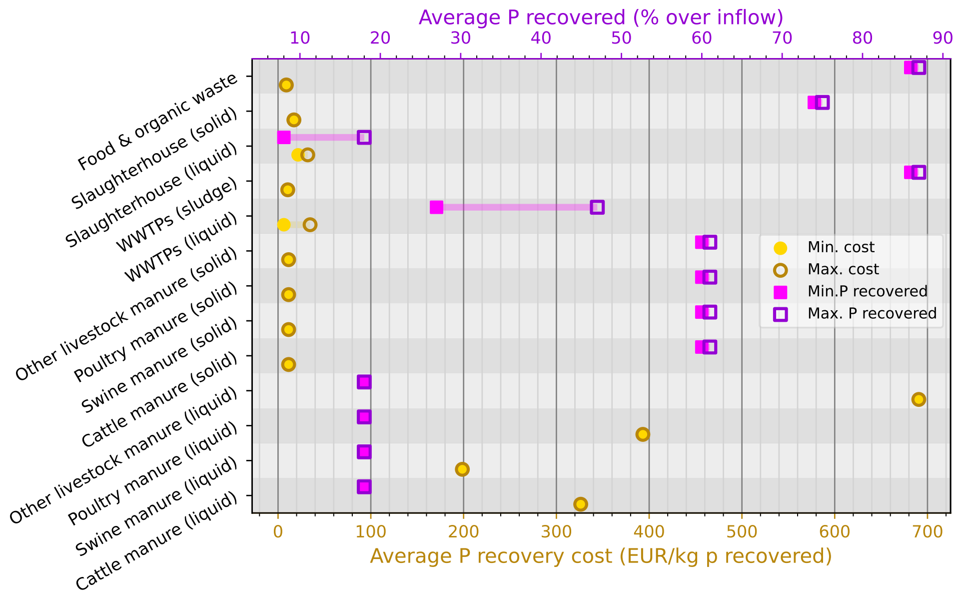

Figure 4: Average phosphorus recovered and average phosphorus recovery cost per kilogram of phosphorus recovered in the province of Ontario by flow.

3.2.1. Agricultural sector

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

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

3.2.2. Industrial and urban sector

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

Slaughterhouse waste is an industrial flow from which phosphorus can be effectively recovered

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

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

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

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

3.3. Economic implications of phosphorus recovery in Ontario

In order to compare the costs derived from the recovery of anthropogenic phopshorus, 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 referred 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 uses of phosphorus, and 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.

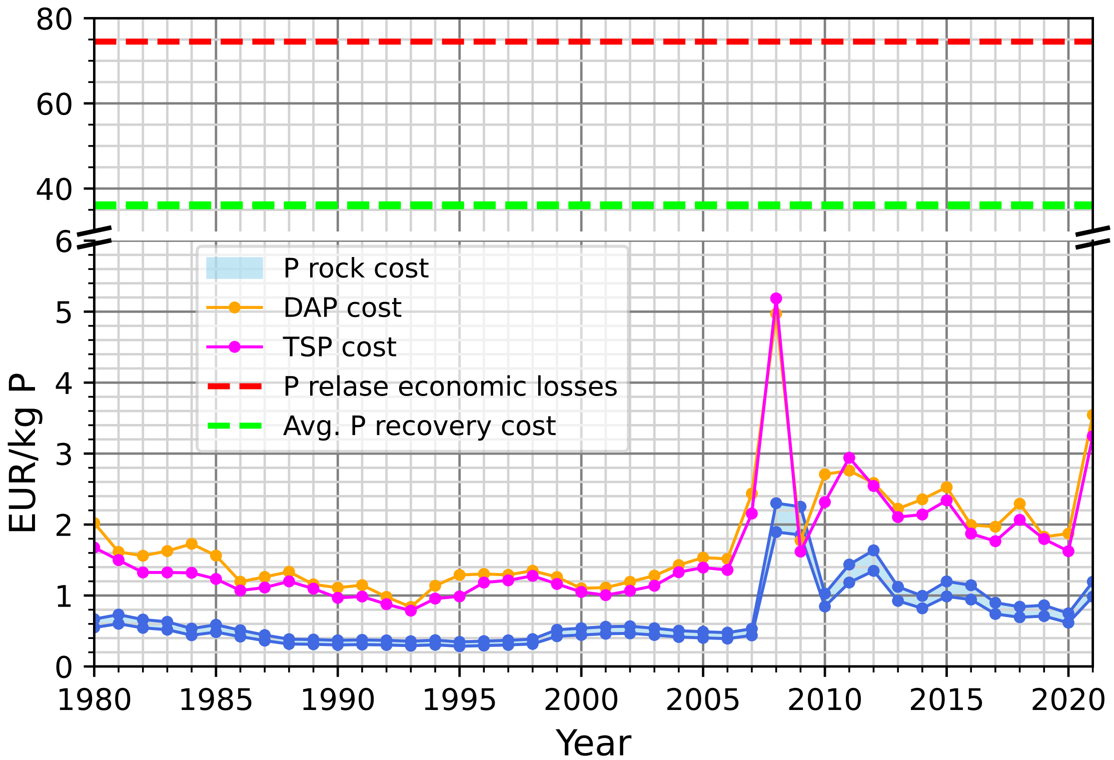

Figure 5: Average phosphorus recovery cost in Ontario, economical losses derived from the releases of phosphorus into the environment (Sampat et al., 2021), and temporal evolution of prices for different phosphorus commodities. Note that the scale of y-axis is different for top and bottom axes.

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 in Ontario's CAFOs. Therefore, regional cooperative strategies can 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 systems, developing a circular economy around the use of phosphorus. 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 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.

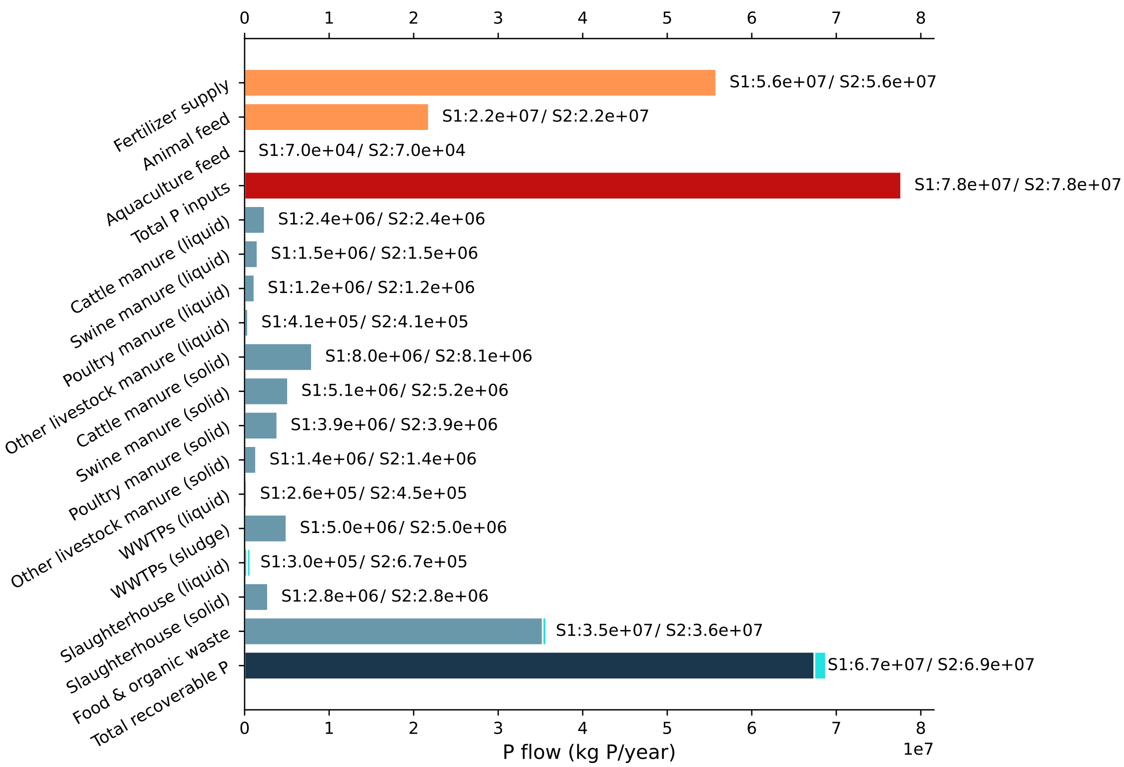

Figure 6: Phosphorus inputs for food production and phosphorus recovered per sector. S1 refers to the scenario minimizing phosphorus recovery cost, while S2 refers to the scenario maximizing phosphorus recovery.

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 CAFOs 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 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 P-surplus 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 economizes of scale for phosphorus recovery. Nevertheless, considering the region studied as a whole, the average phosphosrus 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 ackowledgements

References

Agriculture and Agri-Food Canada, 2021a. Distribution of slaughtering activity. https://agriculture.canada.ca/en/canadas-agriculture-sectors/animal-industry/red-meat-and-livestock-market-information/slaughter-and-carcass-weights/distribution-slaughtering-activity. [Online; accessed 22-August-2022].

Agriculture and Agri-Food Canada, 2021b. Poultry slaughter reports. https://agriculture.canada.ca/en/canadas-agriculture-sectors/animal-industry/poultry-and-egg-market-information/slaughter. [Online; accessed 16-December-2021].

Agriculture and Agri-Food Canada, 2021c. Red meat and livestock slaughter and carcass weights. https://agriculture.canada.ca/en/canadas-agriculture-sectors/animal-industry/red-meat-and-livestock-market-information/slaughter-and-carcass-weights. [Online; accessed 15-December-2021].

Agriculture and Agri-Food Canada, 2021d. Red meat conversion factors. https://agriculture.canada.ca/en/canadas-agriculture-sectors/animal-industry/

red-meat-and-livestock-market-information/slaughter-and-carcass-weights/conversion-factors. [Online; accessed 16-December-2021].

Agriculture and Agri-Food Canada, 2022a. Field crops and hay, Census of Agriculture, 2011 and 2016. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210041601. [Online; accessed 16-December-2021].

Agriculture and Agri-Food Canada, 2022b. Field vegetables,, Census of Agriculture, 2011 and 2016. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210041801. [Online; accessed 16-December-2021].

Agriculture and Agri-Food Canada, 2022c. Greenhouse products and mushrooms,, 2011 and 2016. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042001. [Online; accessed 16-December-2021].

Algoma Steel Inc., 2022. Corporate Profile. https://algoma.com/about-algoma/corporate-profile/. [Online; accessed 13-July-2022].

AMPC, 2018. Struvite or Traditional Chemical Phosphorus Precipitation – What Option Rocks? https://www.ampc.com.au/uploads/cgblog/id408/2018-1026_-_Final_Report.pdf. [Online; accessed 20-March-2019].

van Bochove, E., Thériault, G., Denault, J.T., 2010. Indicator of risk of water contamination by phosphorus (IROWC P): a handbook for presenting the IROWC P algorithms. Technical Report. Agriculture and Agri-Food Canada.

Boh, M.Y., Clark, O.G., 2020. Nitrogen and phosphorus flows in Ontario's food systems. Resources, Conservation and Recycling 154, 104639.

Brake, J., Havenstein, G., Ferket, P., Rives, D., Giesbrecht, F., 1995. Relationship of sex, strain, and body weight to carcass yield and offal production in turkeys. Poultry science 74, 161–168.

Brown, Christine, 2013. Available Nutrients and Value for Manure From Various Livestock Types. Technical Report. Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs.

Brunner, P.H., Rechberger, H., 2016. Handbook of material flow analysis: For environmental, resource, and waste engineers. CRC press.

Bureau, D.P., Gunther, S.J., Cho, C.Y., 2003. Chemical composition and preliminary theoretical estimates of waste outputs of rainbow trout reared in commercial cage culture operations in Ontario. North American Journal of Aquaculture 65, 33–38.

Canadian Forest Service, 2020. Statistical data. https://cfs.nrcan.gc.ca/statsprofile/. [Online; accessed 13-July-2022].

Chambers, J.R., Zaheer, K., Akhtar, H., Abdel-Aal, E.S.M., 2017. Chicken eggs, in: Egg innovations and strategies for improvements. Elsevier, pp. 1–9.

Cheminfo Services Inc., 2019. Economic Assessment of the Integrated Steel Industry. https://www.canadiansteel.ca/files/resources/Final-Report-Economic-Assessment-of-the-Integrated-Steel-Industry.pdf. [Online; accessed 13-July-2022].

Chen, M., Graedel, T., 2016. A half-century of global phosphorus flows, stocks, production, consumption, recycling, and environmental impacts. Global Environmental Change 36, 139–152.

Church, C.D., Hristov, A.N., Kleinman, P.J., Fishel, S.K., Reiner, M.R., Bryant, R.B., 2018. Versatility of the MAnure PHosphorus EXtraction (MAPHEX) System in Removing Phosphorus, Odor, Microbes, and Alkalinity from Dairy Manures: A Four-Farm Case Study. Applied Engineering in Agriculture 34, 567–572. URL: http://elibrary.asabe.org/abstract.asp?AID=48976&t=3&dabs=Y&redir=&redirType=, doi:10.13031/aea.12632.

Cordell, D., Drangert, J.O., White, S., 2009. The story of phosphorus: global food security and food for thought. Global environmental change 19, 292–305.

Du, C.M., Gao, X., Ueda, S., Kitamura, S.Y., 2019. Separation and recovery of phosphorus from steelmaking slag via a selective leaching–chemical precipitation process. Hydrometallurgy 189, 105109.

Du, C.m., Gao, X., Ueda, S., Kitamura, S.y., 2022. Recovery of high-quality phosphate from steelmaking slag by a hydrometallurgical process. Science of The Total Environment 819, 153125.

Egle, L., Rechberger, H., Krampe, J., Zessner, M., 2016. Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. Science of The Total Environment 571, 522–542. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969716314656, doi:10.1016/j.scitotenv.2016.07.019.

Ehlert, P., Morel, C., Fotyma, M., Destain, J.P., 2003. Potential role of phosphate buffering capacity of soils in fertilizer management strategies fitted to environmental goals. Journal of plant nutrition and soil science 166, 409–415.

Environment and Climate Change Canada, 2021a. About the National Pollutant Release Inventory. https://www.canada.ca/en/environment-climate-change/services/national-pollutant-release-inventory/about-national-pollutant-release-inventory.html. [Online; accessed 29-December-2021].

Environment and Climate Change Canada, 2021b. Wastewater Systems Effluent Regulations. https://open.canada.ca/data/en/dataset/9e11e114-ef0d-4814-8d93-24af23716489. [Online; accessed 29-December-2021].

FAO, 2011. Global food losses and food waste - Extent, causes and prevention. https://www.fao.org/3/i2697e/i2697e.pdfg. [Online; accessed 15-July-2022].

FAO & IAEA, 2004. Use of Phosphate Rocks for Sustainable Agriculture. https://www.fao.org/3/y5053e/y5053e00.htm. [Online; accessed 23-August-2022].

Fernández-Delgado, M., del Amo-Mateos, E., García-Cubero, M.T., Coca, M., Lucas, S., 2022. Phosphorus recovery from organic waste for its agronomic valorization: technical and economic evaluation. Journal of Chemical Technology & Biotechnology 97, 167–178.

Food and Agriculture Organization of the United Nations, 2022. The importance of Ukraine and the Russian Federation for global agricultural markets and the risks associated with the war in Ukraine.

Galán-Martín, A., Pozo, C., Azapagic, A., Grossmann, I.E., Mac Dowell, N., Guillén-Gosálbez, G., 2018. Time for global action: an optimised cooperative approach towards effective climate change mitigation. Energy & Environmental Science 11, 572–581.

Government of Canada, 2022. Greenhouse Worker in Ontario - Job prospects. https://www.jobbank.gc.ca/marketreport/outlook-occupation/23339/ON. [Online; accessed 22-December-2021].

Hayse, P.L., Marion, W.W., 1973. Eviscerated yield, component parts, and meat, skin and bone ratios in the chicken broiler. Poultry Science 52, 718–722.

Health Canada, 2008. Nutrient Value of Some Common Foods. https://www.canada.ca/content/dam/hc-sc/migration/hc-sc/fn-an/alt_formats/pdf/nutrition/fiche-nutri-data/nvscf-vnqau-eng.pdf. [Online; accessed 14-December-2021].

Health Canada, 202. Canadian Nutrient File. https://food-nutrition.canada.ca/cnf-fce/index-eng.jsp. [Online; accessed 15-July-2022].

INAC Services, 2014. Poultry processing in Canada. http://inacservices.com/poultry-processing-in-canada/. [Online; accessed 22-August-2022].

Jupp, A.R., Beijer, S., Narain, G.C., Schipper, W., Slootweg, J.C., 2021. Phosphorus recovery and recycling–closing the loop. Chemical Society Reviews 50, 87–101.

Kaiser, D.E., Pagliari, P., 2018. Understanding phosphorus fertilizers. https://extension.umn.edu/phosphorus-and-potassium/understanding-phosphorus-fertilizers. [Online; accessed 23-August-2022].

Martín-Hernández, E., Hu, Y., Zavala, V.M., Martín, M., Ruiz-Mercado, G.J., 2022. Analysis of incentive policies for phosphorus recovery at livestock facilities in the great lakes area. Resources, Conservation and Recycling 177, 105973.

Martín-Hernández, E., Martín, M., Ruiz-Mercado, G.J., 2021. A geospatial environmental and techno-economic framework for sustainable phosphorus management at livestock facilities. Resources, Conservation and Recycling 175, 105843.

National Aeronautics and Space Administration, 2022. Technology Readiness Level Definitions. https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf. [Online; accessed 15-August-2022].

Nesme, T., Metson, G.S., Bennett, E.M., 2018. Global phosphorus flows through agricultural trade. Global Environmental Change 50, 133–141.

Ohtake, H., Tsuneda, S., 2019. Phosphorus recovery and recycling. Springer.

Oldfield, L., Rakhimbekova, S., Roy, J.W., Robinson, C.E., 2020. Estimation of phosphorus loads from septic systems to tributaries in the canadian lake erie basin. Journal of Great Lakes Research 46, 1559–1569.

Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2011. Growing Greenhouse Vegetables in Ontario.

Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2020a. Ontario egg production. https://data.ontario.ca/dataset/ontario-egg-production. [Online; accessed 14-December-2021].

Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2020b. Ontario milk shipments by county. https://data.ontario.ca/en/dataset/ontario-milk-shipments-by-county. [Online; accessed 14-December-2021].

Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2021. Greenhouse Nutrient Feedwater Regulation. http://www.omafra.gov.on.ca/english/nm/regs/gnfpro/gnfreg.htm. [Online; accessed 23-December-2021].

Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2022. Horticultural Crops. http://www.omafra.gov.on.ca/english/stats/hort/index.html. [Online; accessed 18-December-2021].

Ontario Ministry of the Environment, Conservation and Parks, 2012. Greenhouse Wastewater Monitoring Project (2010 and 2011). https://www.ontario.ca/page/greenhouse-wastewater-monitoring-project-2010-and-2011. [Online; accessed 22-December-2021].

Ontario Ministry of the Environment, Conservation and Parks, 2019. Provincial policy objectives for managing effects of cage aquaculture operations on the quality of water and sediment in Ontario's waters. https://ero.ontario.ca/notice/012-7186. [Online; accessed 15-July-2022].

Ontario Ministry of the Environment, Conservation and Parks, 2021. Municipal Treated Wastewater Effluent. https://data.ontario.ca/dataset/municipal-treated-wastewater-effluent. [Online; accessed 29-December-2021].

Opendatasoft, 2019. Census divisions - Canada. https://public.opendatasoft.com/explore/dataset/georef-canada-census-division/table/?disjunctive.prov_name_en&disjunctive.cd_name_en&sort=year&refine.prov_name_en=Ontario. [Online; accessed 29-November-2021].

Pingali, P.L., 2012. Green revolution: impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences 109, 12302–12308.

Pollution Probe, 2022. Mapping Phosphorus Flows in the Ontario Economy. Exploring Nutrient Recovery and Reuse Opportunites in a Provincial Context. https://www.pollutionprobe.org/mapping-phosphorus-flows-in-the-ontario-economy/. [Online; accessed 13-July-2022].

Reid, K., Schneider, K., Joosse, P., 2019. Addressing imbalances in phosphorus accumulation in canadian agricultural soils. Journal of environmental quality 48, 1156–1166.

Reid, K., Schneider, K.D., 2019. Phosphorus accumulation in canadian agricultural soils over 30 yr. Canadian Journal of Soil Science 99, 520–532.

Sampat, A.M., Hicks, A., Ruiz-Mercado, G.J., Zavala, V.M., 2021. Valuing economic impact reductions of nutrient pollution from livestock waste. Resources, Conservation and Recycling 164, 105199.

Sampat, A.M., Hu, Y., Sharara, M., Aguirre-Villegas, H., Ruiz-Mercado, G., Larson, R.A., Zavala, V.M., 2019. Coordinated management of organic waste and derived products. Computers & chemical engineering 128, 352–363.

Sampat, A.M., Martin-Hernandez, E., Martín, M., Zavala, V.M., 2018. Technologies and logistics for phosphorus recovery from livestock waste. Clean Technologies and Environmental Policy 20, 1563–1579.

Samreen, S., Kausar, S., 2019. Phosphorus fertilizer: The original and commercial sources, in: Zhang, T. (Ed.), Phosphorus. IntechOpen. chapter 6.

Sardans, J., Peñuelas, J., 2013. Tree growth changes with climate and forest type are associated with relative allocation of nutrients, especially phosphorus, to leaves and wood. Global Ecology and Biogeography 22, 494–507.

Schoumans, O., Rulkens, W., Oenema, O., Ehlert, P., 2010. Phosphorus recovery from animal manure: Technical opportunities and agro-economical perspectives. Technical Report. Alterra, Wageningen UR.

Senthilkumar, K., Nesme, T., Mollier, A., Pellerin, S., 2012. Conceptual design and quantification of phosphorus flows and balances at the country scale: The case of France. Global Biogeochemical Cycles 26.

Sharma, B.K., Chandel, M.K., 2021. Life cycle cost analysis of municipal solid waste management scenarios for mumbai, india. Waste Management 124, 293–302.

Statistics Canada – Statistique Canada, 2021a. Cattle and calves on census day. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042401. [Online; accessed 29-November-2019].

Statistics Canada – Statistique Canada, 2021b. Other livestock on census day. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042701. [Online; accessed 29-November-2019].

Statistics Canada – Statistique Canada, 2021c. Pigs on census day. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042601. [Online; accessed 29-November-2019].

Statistics Canada – Statistique Canada, 2021d. Poultry inventory on census day. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042801. [Online; accessed 29-November-2019].

Statistics Canada – Statistique Canada, 2021e. Sheep and lambs on census day. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042501. [Online; accessed 29-November-2019].

Statistics Canada – Statistique Canada, 2022. Fertilizer shipments to Canadian agriculture markets, by nutrient content and fertilizer year, cumulative data (x 1,000). https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003901. [Online; accessed 09-February-2022].

Statistics Canada - Statisque Canada, 2015. Sewer and septic system connections. Households and the Environment. https://www150.statcan.gc.ca/n1/pub/11-526-x/2013001/t059-eng.htm. [Online; accessed 15-July-2022].

Statistics Canada - Statisque Canada, 2017. Estimated number of households and average household size by domain, Canada. User guide for the survey of household spending. https://www150.statcan.gc.ca/n1/pub/62f0026m/2017002/app-ann-g-eng.htm. [Online; accessed 15-July-2022].

Statistics Canada - Statisque Canada, 2021. Aquaculture, production and value. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210010701. [Online; accessed 15-July-2022].

Statistics Canada - Statisque Canada, 2022a. Interprovincial and international trade flows, basic prices, summary level. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1210008801. [Online; accessed 13-July-2022].

Statistics Canada - Statisque Canada, 2022b. Livestock estimates. https://www150.statcan.gc.ca/n1/daily-quotidien/220228/dq220228d-cansim-eng.htm. [Online; accessed 15-August-2022].

Statistics Canada - Statisque Canada, 2022c. Population estimates, quarterly. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710000901. [Online; accessed 15-July-2022].

Statistics Canada - Statisque Canada, 2022d. Selected livestock and poultry, Census of Agriculture historical data. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210015501. [Online; accessed 18-August-2022].

Statistics Canada - Statisque Canada, 2022e. Trade Data Online. https://www.ic.gc.ca//app/scr/tdst/tdo/crtr.html?&productType=HS6&lang=eng. [Online; accessed 15-July-2022].

Statistics Netherlands, 2012. Standardised calculation methods for animal manure and nutrients. Standard data 1990–2008. Technical Report. Statistics Netherlands.

Stelco Inc., 2022. Our Facilities. https://www.stelco.com/about-us/our-facilities. [Online; accessed 13-July-2022].

Szögi, A., Vanotti, M., Hunt, P., 2008. Phosphorus recovery from poultry litter. Transactions of the ASABE 51, 1727–1734.

Tan, C., Zhang, T., 2011. Surface runoff and sub-surface drainage phosphorus losses under regular free drainage and controlled drainage with sub-irrigation systems in southern ontario. Canadian Journal of Soil Science 91, 349–359.

The World Bank, 2022. Annual Prices - Commodity Markets. https://www.worldbank.org/en/research/commodity-markets. [Online; accessed 23-August-2022].

Towler, G., Sinnott, R., 2013. Chemical engineering design: principles, practice and economics of plant and process design. Butterworth-Heinemann.

United Nations Environment Programme, 2022. Resolution adopted by the United Nations Environment Assembly on 2 March 2022, UNEP/EA.5 Res.2, on Sustainable nitrogen management.

United States Department of Agriculture, 2009. Agricultural Wate Management Field Handbook. Technical Report. United States Department of Agriculture (USDA).

U.S. Census Bureu, 2021. Current versus Constant (or Real) Dollars. https://www.census.gov/topics/income-poverty/income/guidance/current-vs-constant-dollars.html. [Online; accessed 23-August-2022].

U.S. Department of Agriculture, 2011. Animal Feeding Operations (AFO) and Concentrated Animal Feeding Operations (CAFO). https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/plantsanimals/livestock/afo/. [Online; accessed 10-August-2020].

Van Dijk, K.C., Lesschen, J.P., Oenema, O., 2016. Phosphorus flows and balances of the European Union Member States. Science of the Total Environment 542, 1078–1093.

Van Staden, T., Van Meter, K., Saurette, D., Basu, N., Parsons, C., Van Cappellen, P., 2021. Anthropogenic phosphorus mass balance in ontario counties and watersheds. 10.20383/101.0208.

Villalba, G., Liu, Y., Schroder, H., Ayres, R.U., 2008. Global phosphorus flows in the industrial economy from a production perspective. Journal of Industrial ecology 12, 557–569.

Wang, Y., Zhang, T., Tan, C., Qi, Z., Welacky, T., 2018. Solid cattle manure less prone to phosphorus loss in tile drainage water. Journal of environmental quality 47, 318–325.

World Integrated Trade Solution, 2022. Data on Export, Import, Tariff. https://wits.worldbank.org/. [Online; accessed 13-July-2022].

Yang, J., De Jong, R., Drury, C., Huffman, E., Kirkwood, V., Yang, X., 2007. Development of a canadian agricultural nitrogen budget (canb v2. 0) model and the evaluation of various policy scenarios. Canadian Journal of Soil Science 87, 153–165.

Yokoyama, K., Kubo, H., Mori, K., Okada, H., Takeuchi, S., Nagasaka, T., 2007. Separation and recovery of phosphorus from steelmaking slags with the aid of a strong magnetic field. ISIJ international 47, 1541–1548.

Zagklis, D., Konstantinidou, E., Zafiri, C., Kornaros, M., 2020. Assessing the economic viability of an animal byproduct rendering plant: Case study of a slaughterhouse in greece. Sustainability 12, 5870.

Zhang, T., Tan, C., Zheng, Z., Drury, C., 2015. Tile drainage phosphorus loss with long-term consistent cropping systems and fertilization. Journal of environmental quality 44, 503–511.

Zhou, J., Jiao, X., Ma, L., de Vries, W., Zhang, F., Shen, J., 2021. Model-based analysis of phosphorus flows in the food chain at county level in china and options for reducing the losses towards green development. Environmental Pollution 288, 117768.