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Phosphorus Flow Analysis in Lithuania

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Abstract: Substance flow analysis was used to analyze phosphorus (P) flows, accumulations and losses in Lithuania. P and phosphate rock are included in the list of EU critical raw materials, showing their importance for the EU economy, especially agriculture, and supply risks. It is important to minimize P losses as much as possible, avoid inefficient use, and maximize the potential of secondary P. The analysis showed Lithuania's huge dependence on P imports, which occurred because one of the largest P fertilizer factories operates in the country, and the country also grows and exports a significant amount of cereals. In total, 69% of P addition to soil is from mineral fertilizers. The potential of secondary P is only partially used, mainly via manure, which constitutes 83% of the recycled P and adds 26% of P to agricultural soil. In total, 58% of P "waste" is either lost or accumulated, largely in phosphogypsum stacks. If this P was fully utilized, the country could reduce the current usage of mineral fertilizers by 71%; without P in phosphogypsum, the reduction would be just 7.2%. The P balance in Lithuanian soil is close to neutral. Agricultural leaching and erosion are the main reasons for P entering water bodies (78% of P) and, therefore, should be further reduced.

Keywords: phosphorus; substance flow analysis; material flow analysis; Lithuania; resource management

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1. Introduction

Phosphorus (P) is an irreplaceable nutrient in agriculture, directly impacting food security. Before the 20th century, farmers heavily depended on the natural P present in soil, frequently enhancing it with the regular use of animal manure [1]. The initial chemical fertilizer created through industrial processes was basic superphosphate, manufactured in the early 19th century by treating bones with sulfuric acid. Eventually, the bones were replaced by phosphate rocks. Phosphate rock, however, is a nonrenewable resource. Although P itself is one of the most abundant elements in the Earth's crust, it is only found concentrated in phosphate rock in certain places. The largest known reserves are in Morocco (50,000,000 kt, or 70% of the known reserves) [2,3]. Next comes China and, although China leads the supply of phosphate rock, its reserves (3,200,000) are nearly 20 times smaller than Morocco's. Finland holds the largest reserves of phosphate rock within the EU and stands as the sole member state extracting these resources, contributing to 0.4% of the global production [2,4]. The year 2023 was marked by the discovery of phosphate reserves in another European country: huge phosphate deposits discovered in southwestern Norway [5]. Although P mining is associated with certain negative environmental impacts, this discovery is still good news for Europe, as it may provide some autonomy and ensure the availability of phosphates for fertilizer production as well as other important uses. P significance extends beyond food production, encompassing various industrial and technical applications such as flame retardants, batteries, photovoltaics, industrial water treatment, and emulsifying agents [2].

The estimated lifespan of P reserves varies significantly, spanning from hundreds to thousands of years [3,6]. Regardless of which assessments are true, the circularity of P is important both for protecting resources and for avoiding P entering water bodies, because

P has its "dark side". Phosphorus, along with nitrogen, contributes to the eutrophication and impairment of numerous surface, coastal, and even marine water ecosystems [4,7]. The Baltic Sea is one such water body that is affected by eutrophication. This was recognized in the 1980s, although excessive inputs of nutrients to the sea have occurred since the middle of the 20th century. To address human-induced impacts, measures were set to reduce nutrient loading by 50%, as agreed upon in the 1988 HELCOM Ministerial Declaration [8]. Achieving a Baltic Sea free from eutrophication was identified as a goal in the 2007 Baltic Sea Action Plan (BSAP) [9]. The updated BSAP in 2021 [10,11] assesses individual countries' progress toward their designated nutrient reduction targets through a follow-up system based on nutrient input ceilings (NIC) specific to each country within Baltic Sea sub-basins. The results for the assessment period 2016–2021 revealed that eutrophication remains a significant concern in the Baltic Sea, although, in general, nutrient inputs to the Baltic Sea have decreased [7]. In fact, the input ceilings fulfillment was achieved not in all sub-basins and not by all the countries [12]. For example, Lithuania fulfilled the input ceiling for P for the Gulf of Riga but exceeded it for Baltic Proper.

To address supply risks and the importance of phosphate rock and P for the EU economy, both are included in the list of EU critical raw materials [13]. Responding to the importance of P as a raw material and the environmental impact of P, some countries in the Baltic Sea region have already taken steps towards sustainable P management, where P is part of a circular economy. Examples are the regulatory framework of Germany, which provides requirements to recover and reuse P from waste streams (wastewater sludge or mono-incineration ash) as fertilizer, and the functioning installations for P recovery from various waste, again in Germany and also Denmark [4,14]. Animal manure, urban wastewater, and solid and liquid waste from food processing, such as slaughter waste, have potential for secondary P. When providing recommendations and practical actions for more sustainable P management in the Baltic Sea region countries, Smol et al. [4] noticed the importance of deep analysis of P flows on the regional and national levels. Material flow analysis (MFA) for each Baltic country was proposed. Various P flow analyses have been conducted and are available in scientific publications for Denmark [15], Finland [16,17], Germany [18], and Sweden [19,20]. However, information on P flows in countries east of the Baltic Sea is scarce and fragmentary.

The fact that P is an essential and nonrenewable resource is not only important for Europe. Phosphorus flows have been analyzed by scientists from many countries in the world, e.g., China, New Zealand, Thailand, etc., in order to understand and assess the situation in their countries and to provide recommendations for sustainable phosphorus management [21–24]. Each country has its own characteristics but the common point is that the potential of secondary P is still not exploited and the management of P is not yet sustainable.

Although Lithuania, like most European countries, does not have primary P resources, in 1963, the country started producing mineral P fertilizers and it used to be among the three to four main producers of diammonium phosphate globally [25]. The whole of Lithuania falls within the territory of the Baltic Sea basin. As the sea is affected by eutrophication, it is important to reduce the input of nutrients to the sea as required by HELCOM, in particular HELCOM BSAP [10]. The aim of the conducted study was to identify and quantify P flows, changes in stocks and balances in Lithuania, and to understand how closed the P flows in Lithuania are; all these serve as a first step for resource optimization and aid implementation of circular economy solutions.

2. Materials and Methods

Material flow analysis (MFA), which can be called substance flow analysis (SFA) when namely a substance is analyzed, was used in this study [26,27]. As stated in [27], "material flow analysis is a method to describe, investigate, and evaluate the metabolism of anthropogenic and geogenic systems". Software STAN 2.5 was used to visualize P flows, consider uncertainties, reconcile data, and calculate P balances.

2.1. Description of the System

The geographical boundaries of the analyzed system cover the territory of the Republic of Lithuania. The conceptual model of Lithuanian P balance was developed on the example of the European P balance [28], with further adaptation to the Lithuanian circumstances. Hydrosphere, which is included as one of the processes, is outside the system. It represents a natural environment and collects P, which reaches the environment via discharges, effluents, and leaching. Atmospheric influence is assumed not to be big; it is more substantial in South Europe according to [29] and atmosphere is, therefore, not included in this study.

Flows and accumulations were calculated for a one-year period. To level out short time fluctuations, the average values were calculated from the period of 2018 to 2020. Still, this is a static model, which reflects a situation at a certain moment instead of demonstrating trends and forecasts.

Stocks within the system were not included in the analysis, as the uncertainties of their values are huge while the contribution of flows during one single year is much smaller than the stocks. Thus, it was not the stocks themselves that were important in the analysis but, rather, P flows and changes in P stocks.

The main considered processes were agriculture, trade industry commerce, separately distinguished fertilizer production due to the significance of this process in terms of P amounts, consumption, wastewater treatment, waste management, and industrial waste management of fertilizer production. Subsystems agriculture and waste management were analyzed more in detail. In total, 51 various flows link the processes.

In the analyzed period, Lithuania had about 2.8 million inhabitants and 2950 thousand hectares of agricultural land [30]. These numbers were used to calculate the per capita and per hectare figures used for comparisons.

2.2. Data Collection and Uncertainty Assessment

Statistical databases, data published by economic entities, and practical and scientific literature were reviewed when collecting the data. Specifically, the major part of the data on material flows was retrieved from Indicators database of Official Statistics Portal, Lithuanian Environmental Protection Agency, Regional Waste Management Centers, Center for Agricultural Information and Rural Business, Eurostat databases, company AB Lifosa, etc. Information on P concentrations in various materials was collected from literature sources. Priority was given to national databases and research conducted in Lithuania.

To quantify the flows, the material flows were multiplied with their P concentrations. In some cases, data were available directly as amount of P per year (e.g., P in wastewater). In a few instances where data were unavailable, expert opinions and the principle of mass balance were utilized to estimate the missing flows. Some P flows were cross-validated through the comparison of their values using alternative data sources.

To estimate uncertainties in P flows, the uncertainty concept utilized and described in previous P flow studies was used [15,24,31]. The concept developed by Hedbrant and Sörme [32] was further developed by other researchers, including Laner et al. [33] modification for use with STAN software. It is based on the categorization of data sources. Each data set is assigned an uncertainty level and receives coefficient of variation (CV). The more reliable the data, the lower the level of uncertainty and the coefficient of variation. CVs were assigned both to material flow and P concentration and then calculated for the P flow, unless data were readily available on P flow. When calculating with STAN, data reconciliation is weighted by uncertainty, prioritizing highly uncertain data for reconciliation. This study categorized data sources into 4 uncertainty levels, as presented in Table 1.

Detailed information on all the flows, assumptions made in their calculations, data sources, uncertainties, and initial and reconciled values are presented in Table S1 of Supplementary Materials.

Table 1. Categorization of data sources into uncertainty levels and the corresponding coefficients of variance (CV) used in this study.

Uncertainty Level	CV, %	Explanation
1	15%	Official statistics, small data set variability. Targeted scientific or technical report values.
2	30%	Official statistics, bigger data set variability. Using scientific literature or technical report data but certain assumption required.
3	45%	Scientific or technical report data averages from big data variability.
4	60%	Estimates

3. Results

The calculated Lithuanian P balance is presented in Figure 1. The quantity of each flow, expressed as t P/year, is accompanied with an uncertainty. Further in the text, for clarity reasons, the flow and accumulation values are presented without their uncertainty.

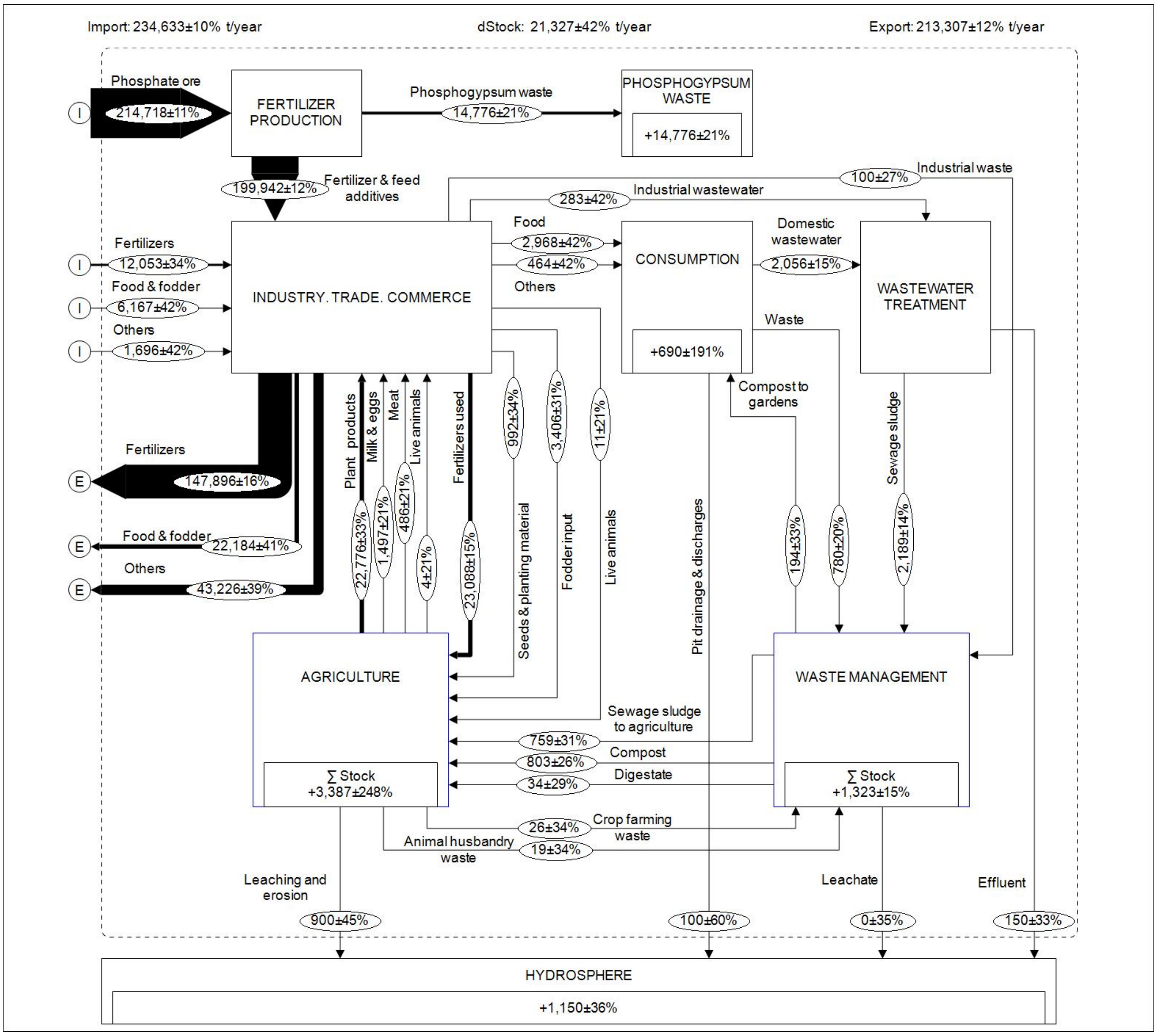

Figure 1. Lithuanian phosphorus (P) budget. Values reconciled with STAN and cover a one-year period during 2018–2020. Values expressed as t P/year and uncertainty in percent. I—import, E—export.

3.1. National Phosphorus Balance and the Main Flows

The total P inflow to Lithuania was 234,633 t/year. The largest part of this total amount, as much as 91.5%, came from the import of phosphate rock. Fertilizer import was 5.1%, food and fodder was 2.6%, while others (non-food commodities) constituted just 0.7% of the total amount.

The flows related to phosphate rock processing are the largest in the case of Lithuania, both in terms of imports and exports, as well as internal flows and accumulation. The total export was 213,307 t, primarily as fertilizers (69.3%), other goods with a domination of monocalcium phosphate and monoammonium phosphate used as raw material for animal feed (20.3%), and feed or fodder (10.4%). The accumulated stock was 21,327 t, mainly within phosphogypsum waste (69.3%), which equals a net accumulation of 7.6 kg P/capita. This is a high value compared to 4.3 kg P/capita and 4.9 kg P/capita, which was reported for European Union (EU) countries [28,34]. However, after deducting the accumulation in phosphogypsum from all accumulations, only 2.3 kg P/capita remains, which is half as much as the average of EU countries.

Losses to the environment mean that P reaches the hydrosphere. The main contributor to the total 1150 t P losses to water bodies was leaching and erosion from agriculture (900 t P, or 78%).

3.2. Fertilizer Production and Other Industry, Trade and Commerce

P fertilizer production is an important industry in the country; Lithuania was among the five top producers that collectively account for 98.2% of diammonium phosphate production globally [25]. The big production volume was the reason for substantial import and export flows as well as accumulation in stock, i.e., phosphogypsum waste. Phosphogypsum waste accounts for about a quarter of all waste generated in the country [35]. Phosphate rock import to Lithuania was mainly from Russia (~65%), as well as from South Africa, Morocco and other countries [4,30]. In total, 93–98% of company production went to export [36]. Interestingly, Lithuanian agriculture needs were satisfied not just by local production but also from the import.

The other industries and trade, which contribute to P flows and were included in the analysis, are food, chemical industry (e.g., detergents), planting materials and live animals, chemicals for laboratory usage, etc. Nevertheless, none of these processes is comparable in size to phosphate rock processing.

Export of P in food was higher than import of P in food. The reason is the cultivation of wheat and rapeseed. A large part of these crops (85% of wheat and 54% of rapeseed), which accumulate significant amounts of P, are exported.

3.3. Agriculture

Flows that reach and leave agricultural soil as well as animal husbandry are presented in Figure 2. The number of animals and poultry is decreasing in the country, but the raised live weight of animals and birds has somewhat increased during the analyzed period [30]; therefore, the animal husbandry stock was assumed constant. Livestock density in Lithuania is one of the lowest in the EU, 0.2 livestock units per hectare of utilized agricultural area (LSU/ha UAA), while the EU average was 0.7 LSU/ha UAA in 2020 [37]. Although almost all manure produced is spread on agricultural fields, the low number and density of livestock meant a relatively low amount of available manure that could be spread. Input of manure was 2.9 kg P/ha agricultural land. The other important inputs of P to agricultural land were mineral fertilizers (7.8 kg/ha), compost (0.28 kg/ha), and sewage sludge (0.26 kg/ha). Reliance on mineral fertilizers (69% of inputs) is thus high in Lithuania. Losses due to leaching and soil erosion (0.3 kg/ha) and P removal with plant harvest and fodder (10.2 kg/ha) resulted in a positive P balance of 1.15 kg/ha.

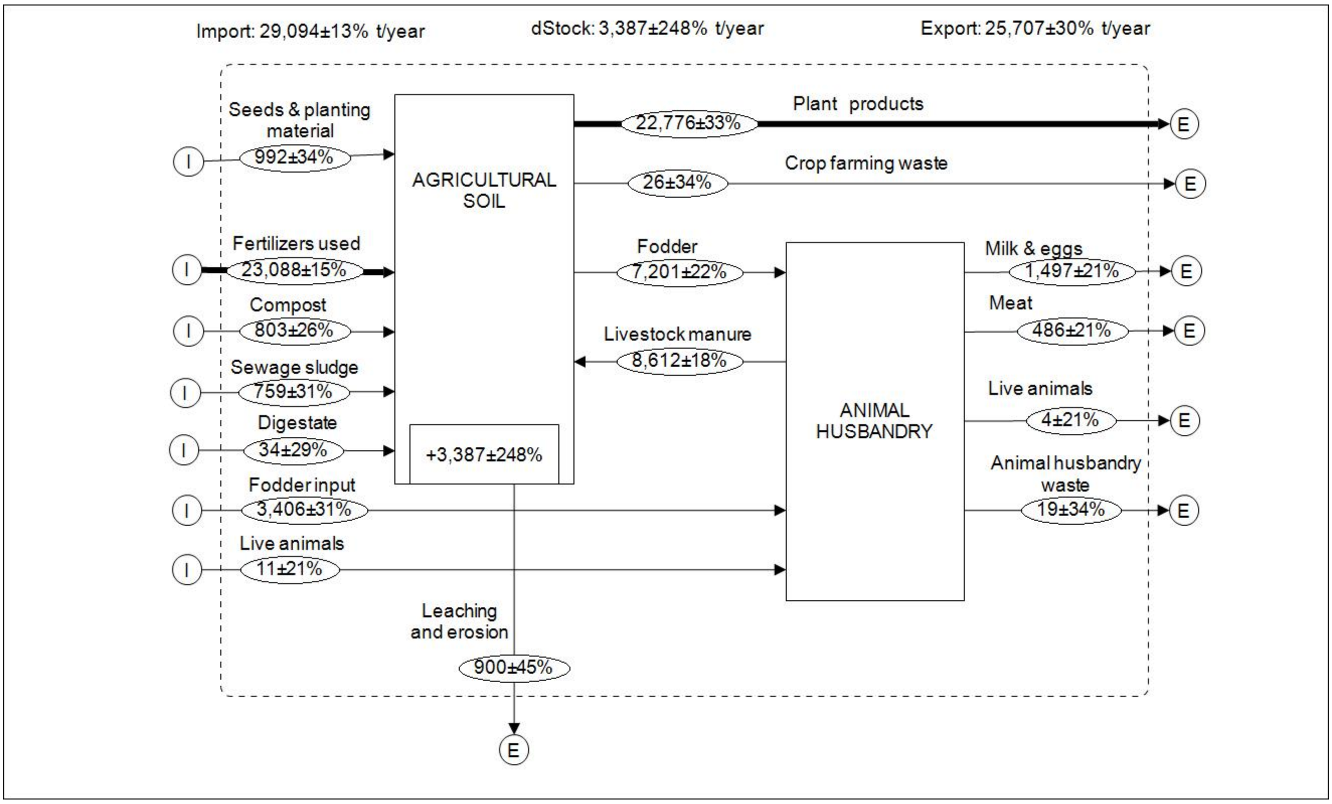

Figure 2. Agricultural subsystem of phosphorus flows.

Lithuania is a country where both P inputs and outputs are lower than the EU average for agricultural soils [34,38–41] (Table 2). Compared to other countries, the most similar situation is observed in Latvia and Estonia. In the Baltic Sea region, a somewhat similar situation is also found in Sweden and Finland, while Poland and Denmark are characterized by much larger inflows and outflows, as well as accumulations. The current study estimated a little positive balance, 1.15 kg/ha, but P accumulation in Lithuanian soils over longer periods seems to be neutral, i.e., neither P surplus nor deficit. For example, OECD estimates suggest 0.4 kg/ha balance in 2018 and −1.3 kg/ha in 2019 [42].

Table 2. Agricultural soil P balance comparison with EU situation.

	Lithuania, This Study, 2018–2020	**Average for EU, (Ranges in Different Countries), (Assessment for Lithuania)**	
		[38], 2010–2019	**[29], 2011–2019**
	kg/ha per Year		
P input	11.3 [1]	13.0 [2] (4.4–23.6) (LT: 7)	15.2 [3] (5.8–25) (LT: 10.2)
Input from mineral fertilizers	7.8	6.4 (1.73–9.92) (LT: 5.17)	7.6 (<4.0–>9.0) (LT: 6.5–7)
Input from manure	2.9	6.5 (1.1–18.1) (LT: 2.2)	7.6 (<2.5–>15.0) (LT: 2–3.5)

Table 2. *Cont.*

	Lithuania, This Study, 2018–2020	Average for EU, (Ranges in Different Countries), (Assessment for Lithuania)	
		[38], 2010–2019	[29], 2011–2019
	kg/ha per Year		
Harvested P (removal with plants)	10.2	12.6 (<10.0–>19.0) (LT: 7–9)	14 (<7.0–>25.0) (LT: 13–15)
Balance	1.15	0.11 (−2.5–5.2) LT: 0.7	0.8 (−6.9–12.3) (Lt: −3.4)

[1] Includes mineral fertilizers, manure, compost, and sewage sludge. [2] Includes mineral fertilizers, manure, and chemical weathering. [3] Includes mineral fertilizers, manure, atmospheric deposition, and weathering.

The efficiency of the Lithuanian agricultural system in converting P inputs within mineral and organic fertilizers into plants was around 90%, which can be judged as a rather high value. Two crops accumulated most of the total P used in crop production. Cereals, especially wheat, dominated the accumulation of P in plants. About 49% of P in plants was namely P in wheat. Rapeseed was the second most P-accumulated crop, with 26% P.

P input to animals consisted of P in fodder and P in grazing grasses and totally made up 10,607 t of P. The main outputs were animal products (1987 t P) and manure. The efficiency of converting P inputs into animal products was thus around 19%. As for the animal husbandry profile, the total P amount in milk and eggs was about 3 times more than P in meat.

3.4. Consumption

Consumption received 3626 kg P, of which 82% was in food. When translated into per capita consumption, 1.06 kg P was in food, 0.17 kg P in non-food products, and 0.07 kg P in home-composting compost. Non-food comprised a variety of products, such as detergents, home plants, P in products, and P in straw (e.g., straw roofs). The accumulated amount can be attributed namely to consumption of the products that last longer than a year, including non-food consumption but potentially also food preserves.

3.5. Water Treatment

The processing industry, including the food industry, which would release wastewater with P, was not very large in Lithuania; the amount of P in domestic wastewater was about 7 times higher than that from industry. The 150 t P remaining in the wastewater that was discharged from wastewater treatment plants (WWTPs) shows a high treatment efficiency, about 93%. According to the provisions of the Urban Wastewater Treatment Directive (UWWTD), the territory of Lithuania is classified as a sensitive area due to the eutrophication of the Baltic Sea, which is sensitive to emissions of nitrogen and phosphorus, and a tertiary treatment must be applied in agglomerations larger than 10,000 population equivalents (p.e.). WWTPs of 10,000–100,000 p.e. have achieved 91.4%, and WWTPs >100,000 p.e. achieved 96.0% purification [43]. P from wastewater enters sewage sludge.

However, not all residents are connected to centralized wastewater treatment. On the national scale, including those residents where >2000 p.e. agglomerations are not formed, the connection to centralized networks in 2019 reached 76.45% [43]. Pit drainage and discharge was estimated to be 100 t P/year.

3.6. Waste Management

A total of 3113 t P/year entered waste management processes (Figure 3). Of this, 57.5% (1791 t) was returned to the system. About 194 kg P, or 6.2% of P in waste, reached home gardens in the form of compost. The biggest share was returned to agriculture, in total, 1596 t P (51.3% of P in waste). This represented 4.8% of inputs into agricultural crop production.

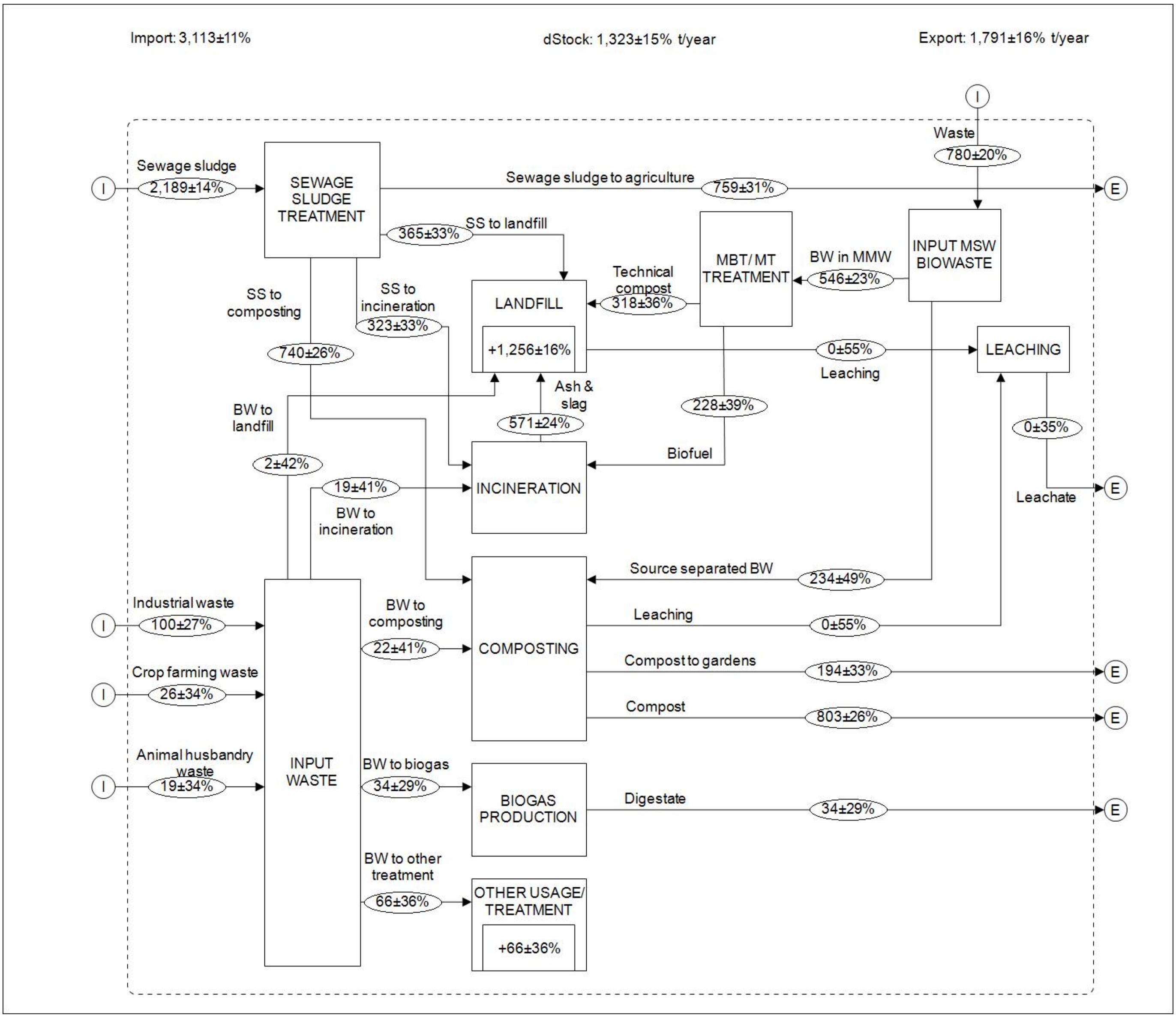

Figure 3. Waste management subsystem of phosphorus flows. BW—biowaste, MBT/MT—mechanical biological treatment/mechanical treatment, MMW—mixed municipal waste, MSW—municipal solid waste, SS—sewage sludge.

In comparison with other countries in the Baltic Sea region, 0.28 kg/ha of compost is spread in Lithuania, while, in Sweden, it is 0.4 kg/ha; in Germany, 0.9 kg/ha; and in different regions of Denmark (adding compost and digestate together), 0.27 kg/ha, 0.5 kg/ha, and 0.62 kg/ha [15,44]. The used amounts of sewage sludge were very similar to those of compost within each of the countries: in Lithuania, 0.26 kg/ha; in Sweden, 0.4 kg/ha; in Germany, 0.9 kg/ha; and in different regions of Denmark, 1.33 kg/ha, 0.87 kg/ha, and 0.68 kg/ha.

Agricultural (nevertheless, agricultural waste that is utilized/recycled in the farms themselves is not included in flows that leave the process agricultural soil), industrial, and green waste, as well as sewage sludge, were used for the production of compost in Lithuania. About 34.1% of sludge in the country was directed to composting. In total, 34.5% of the sludge was diverted to agriculture directly. However, the flow of sewage sludge to both uses has decreased significantly in recent years as more and more sludge is diverted to incineration. The share of incinerated sludge increased from 4.3% in 2018 to 35.2% in 2020 [35]. The resulting ash goes into either cement when incinerated in a cement plant or to landfill. There were no mono-incineration processes in the country and P extraction from ash was not carried out [43]. In total, 16.6% of the sludge was still directed to landfills or storage sites.

Input waste from industry and agriculture was distributed over a variety of treatment methods. Anaerobic digestion was not very widespread in the country yet. Landfilling was already minor. Statistics also identified “other treatment”, without specifying what is behind it [35]. Thus, there is an accumulation of 66 t of P, which could be laid out more clearly.

A large part of the municipal biowaste was collected with the mixed waste and sent to mechanical biological treatment for the separation of the biological part. There are 10 waste management regions in Lithuania that have different decisions on what to do with the separated fraction of biowaste. Biofuel is obtained in some places and technical compost is obtained in others after aerobic or anaerobic treatment. Technical compost is used to cover landfill layers. The use of this compost in agriculture is not possible due to its insufficient quality. Thus, the biowaste was stabilized, the uncontrolled release of greenhouse gases into the atmosphere was prevented, but the opportunity to recover nutrients, including P, was lost. Landfills also received ash from waste incineration. Thus, 1256 t of P were filled into the landfills during the year, and that was 40% of the total P that entered the waste.

Leaching from waste management sites was assessed to be 0.3 t/year, which is not much due to the implemented good practices and control.

4. Discussion

The P flow analysis provided key information on major P flows, accumulation, and losses. In the European context, Lithuania had very high P import (83.8 kg/capita) and export (76.2 kg/capita) flows (Table 3). This was related to participation of the country in the global P cycles via production and supply of P fertilizers rather than to internal consumption in agriculture, the domestic sector, or industry other than fertilizers.

Table 3. Lithuanian P import from and export to other countries vs. import and export in Europe and other countries in the Baltic Sea Region.

Country, Region	Year	Import	Export	Taken from, or Calculated on the Basis of:
		kg P/Capita		
Lithuania	2018–2020	83.8	76.2	this study
EU-15	2007	5.19	0.89	[28]
EU-27	2005	4.9	3.0	[34]
Denmark	2011	10.2	6.5	[15]
Sweden	2017	2.7		[20]

The most substantial accumulation, 14,776 t P/year, occurred in the piles of phosphogypsum (PG) waste. Despite ongoing scientific research, e.g., [45,46], only a very minor amount of PG was recycled in construction and agriculture [47]. The total amount of PG currently exceeds 21 million tonnes [45], pointing to the need for cost-effective technological solutions for the recovery of materials or for technological applications. Worldwide, only some 14% of PG are further processed [48]. The main part of the used phosphate rock in the case of Lithuania was sourced from Kola Peninsula in Russia. It is of magmatic origin and, therefore, the issue of radioactivity does not have such relevance as in the case of sedimentary rock [48]. Thus, regarding recovery, it could, for example, be rare earth elements but maybe P itself via PG usage for agricultural purposes. PG waste can be seen both as an environmental problem and one of the factors that reduces circular material use rate of the country currently [47] but also has potential in the future.

Due to the geopolitical situation resulting from Russian aggression against Ukraine, the ties of the company with certain owners, and the introduced sanctions, the company has had difficulties with its functioning since 2022.

Agriculture was the second major user of P in the country. As indicated under 3.3 Agriculture, P balance in soil was close to neutral and the efficiency in converting P inputs into plants was high (90%). Nevertheless, SFA revealed only a general picture, while differences might occur across the country. According to [49], this was exactly the case. Soils conditionally rich in P (P_2O_5 >150 mg/kg) constitute 30% of soils, while 49.7% are those with low and very low content (<100 mg/kg). The soils of central Lithuania have the most phosphorous. In this area, 27.3% have more than 200 mg/kg, and only 4.4% have very little P. The least rich in P are soils in the west, where even 71.5% have low and very low P content. It would be necessary to fertilize with P fertilizers less in central Lithuania but, as highlighted in [49], in practice, the situation is the opposite. During the last 10 years, as a result of fertilization, the areas of relatively phosphorus-rich soils in central Lithuania have increased, while, in eastern and western Lithuania, they have decreased.

Although the efficiency is good and over-fertilization is not a country-wide problem, it rather occurs in certain areas only, agricultural leaching and erosion are the main reasons for P entering water bodies (78% of P reaching water bodies). Best management practices for non-point-source agricultural water pollution control have to be applied in order to further reduce leaching and erosion [50]. Further potential to reduce losses of P is represented by taking care of pit drainages and discharges by further connecting households to the centralized sewage networks and paying proper attention to those having individual treatment facilities. Considering the achieved treatment efficiency (93%), discharges from WWTPs seem to have limited remaining potential for further improvement.

Most P from wastewaters ends up in sewage sludge. Around 68.6% of P present in sludge is returned to agricultural land, while the rest is lost via incineration or landfilling. This amount, if it was all used in agriculture, could replace about 3% of used mineral fertilizers. Another 1.4% of mineral fertilizers could be replaced by compost if the municipal waste management system works in such a way that high-quality compost is produced from biodegradable waste instead of technical compost. To achieve this, biodegradable waste, such as food waste, should be collected separately and directed to appropriate treatment. Finding even more secondary sources of P that could replace mineral fertilizers would not be easy. P in industrial waste, which is lost due to incineration or landfilling, would not make up even a percent of the amount of mineral fertilizers currently used. P in industry-related waste and wastewater flows are low in Lithuania. One of the explanations can be industry and agriculture profile of the country. The livestock and meat industry sector is not large and has a tendency to continue to shrink [30]. The fact that relatively few animals are kept in the country also determines the limited amount of manure and slurry. Although most of the manure is spread on the fields, the P content of the manure is still more than half compared to mineral fertilizers.

Another feature of the country is the cultivation of cereals, mainly wheat. Lithuania is among the countries that export the most wheat in the world, ranking around 14th place among exporters in individual years [51]. Cereals are a crop that accumulates a lot of P. This circumstance, together with significant exports, leads to the fact that 7.9 kg P/capita per year was brought out of the country with food products, which is 3.6 times more than P imported with food.

5. Conclusions

P flows in Lithuania have several interesting features. Significant exports, imports and accumulations were determined by the production of P fertilizers, as the company located in Lithuania is one of the largest producers of P fertilizers in the world. Another feature is the significant export of P from the country with food, as the country is among the largest wheat growers and exporters. The mentioned flows are significant both in absolute terms and especially per capita, since the country's population is small, less than 3 million.

The analysis of P flows over a short period in this study showed a slight positive P balance in the soil but, when compared with statistical data and other studies, it can be seen that the overall P balance in the soil is neutral in the longer term. Mineral fertilizers were the main source of P addition to the soil, accounting for about 69%. Nearly all manure and slurry in the country was spread on agricultural fields but, due to the relatively small number of livestock, this accounts for 26% of soil inputs. Still, manure constituted the largest share of the recycled P (83%). P from compost and sewage sludge made up the remaining inputs.

In total, 58% of P "waste" was either lost or accumulated, largely in phosphogypsum stacks. If this P was fully utilized, the country could reduce the current usage of mineral fertilizers by 71%; without P in phosphogypsum, the reduction would be just 7.2%.

Thus, the existing agricultural profile, when large quantities of cereals and rapeseed are grown and exported and animal husbandry is comparatively small, in combination with industry profile and small country population, leads to dependence on mineral fertilizers.

Losses of P to water bodies amounted to 0.41 kg/capita. Further reduction potential exists in the application of good agricultural practices and the avoidance of drainage and discharges from pits.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16146001/s1, Table S1: Explanation of flows: assumptions made, references, entered and reconciled values, including uncertainties (coefficients of variation (CV)). References [52–78] are cited in the Supplementary Materials.

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